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Departmental Report

INVESTIGATION OF THE STABILITY AND CONTROL CHARACTERISTICS
OF SEVERAL CONFIGURATIONS OF THE DARPA SUBOFF MODEL
(DTRC MODEL 5470) FROM CAPTIVE-MODEL EXPERIMENTS

by

Robert F. Roddy

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A program of straightline captive-model experiments was performed in the vertical and horizontal planes of motion at deep submergence to determine the stability and control characteristics of the DARPA SUBOFF model. The experiments were performed for the following configurations: (1) the model fully appended in the vertical plane of motion, (2) fully appended in the horizontal plane, (3) unappended hull, (4) hull plus sail, (5) hull plus control surfaces, (6) and hull plus ring wing (Number 1). The results of the experiments indicate that the model is unstable in all of the conditions investigated.

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ABSTRACT

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ADMINISTRATIVE INFORMATION

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INTRODUCTION

The Submarine Technology Program (STP) Office of the Defense Advanced Research Projects Agency (DARPA) funded the Computational Fluid Dynamics (CFD) Program to develop methods that could be used in the design of future advanced submarines. The SUBOFF project was developed to evaluate various flow field predictions for an axisymmetric hull, both with and without appendages. It was intended to compare the predictions with model experimental data.

As discussed in Reference 1, the hull and the appendages of the SUBOFF model were designed by the David Taylor Research Center (DTRC). Various experiments were planned for the model, and the programs for these experiments as well as the facilities in which they were to be performed are discussed in Reference 2. This report provides the results of the stability and control experiments.

The program of straightline captive-model experiments was performed in the vertical and horizontal planes of motion at deep submergence to determine the stability and control characteristics of the DARPA SUBOFF model. The tests were performed for the following configurations which do not include a propeller:

Number	Plane of Motion	Hull	Sail	Stern Appendages	Ring Wing No. 1
1	vertical	x	x	x	x
2	horizontal	x	x	x	x
3	horizontal	x			
4	horizontal	x	x		
5	horizontal	x		x	
6	horizontal	x			x

Measurements were also made of the normal force, longitudinal force, spanwise

center of pressure, and stock torque developed on the upper rudder for the horizontal plane experiments, and the port sternplane for the vertical plane experiments. These measurements were made using a control surface stock instrumented with five strain gages.

This report describes the model, outlines the experimental procedures, presents the experimental data in graphical and tabular form, and provides a brief discussion of the results.

DESCRIPTION OF THE MODEL

The geometric characteristics of the DARPA SUBOFF model are given in Table 1 and the offsets of the hull are given in Table 2. The overall length of the DARPA SUBOFF submarine model is 14.2917 feet (4.356 m), while the length between perpendiculars (the characteristic length used for nondimensionalization of the hydrodynamic forces and moments is 13.9792 feet (4.261 m). The maximum diameter is 1.667 feet (0.508 m).

The submarine model is a body of revolution, which has a sail, no forward planes, conventional cruciform stern composed of four identical all-movable planes, and a ring wing supported by four struts in an "X" configuration. The DARPA SUBOFF is represented by DTRC Model 5470 which is manufactured of fiberglass. A drawing of the submarine showing the principal dimensions is given in Figure 1 and drawings of the sail and stern appendages are given in Figures 2 and 3, respectively. Figure 4 presents a photograph of Model 5470.

TEST APPARATUS AND PROCEDURES

The experiments were performed in the David Taylor Model Basin on Towing Carriage 2 using the Planar Motion Mechanism which is described in References 3, 4 and 5. A sketch of the apparatus with a model attached is shown in Figure 5. A schedule of the stability and control experiments is presented in Table 3.

The model was supported by two vertical struts in tandem, spaced 6 feet (1.83 m) apart. The reference point was located midway between the struts at a point 6.6042 feet (2.013 m) aft of the forward perpendicular (nose) on the hull centerline. The location of the reference point did not correspond with the longitudinal location of the center of buoyancy for any of the configurations evaluated.

The force gages which were located at each strut were used for measuring the longitudinal, normal, and lateral force components with respect to the body axes. The pitching moment about the reference point was determined from the difference in the measured reaction forces at each strut multiplied by one half the strut spacing.

The port sternplane stock was instrumented to determine the longitudinal and normal forces, the stock torque, and the spanwise center of pressure on the control surface for the vertical plane experiments conducted on Configuration

1. The upper rudder was instrumented to determine the longitudinal and lateral forces, the stock torque, and the spanwise center of pressure on the control surface for the horizontal plane experiments conducted on Configurations 2 and 5.

The model was towed inverted for all vertical plane experiments and starboard side down for all horizontal plane experiments. During an experimental data run, the gage output signals were monitored by electronic display on a Data Acquisition Data Logger described in Reference 5. The signals were also input to a digital mini-computer (except for oscillation data) where tares were removed and the measurements nondimensionalized according to the procedures provided in References 3 and 4.

The static stability experiments were conducted at a model speed of 6.5 knots which corresponds to a Reynolds number (based on the length between perpendiculars) of about 14 million.

Captive-model experiments have been performed with various submarine designs to investigate the effect of scaling on the hydrodynamic forces and moments developed on the hull and appendages either at an angle of attack or with a control surface angle. These experiments indicate that the nondimensional hydrodynamic force and moment coefficients vary with Reynolds number up to a Reynolds number based on the length of the hull of about 10 to 15 million, but above this value the coefficients no longer significantly change with Reynolds number. Based on comparisons between either captive-model or radio-control model data and full-scale trials, if model experiments were performed at or above a Reynolds number of 10 to 15 million, then scale effects between model and full-scale would be negligible for the purpose of making stability and control predictions.

REDUCTION AND PRESENTATION OF DATA

The hydrodynamic force and moment measurements were nondimensionalized using the length between perpendiculars of 13.9792 feet (4.261 m). The notation used in this report is given in Reference 6.

The nondimensional data are presented in graphical and tabular form in Appendices A (Figures 6 through 64) and B, respectively. Tares have been removed from the data obtained from the static stability and control experiments, but not from the data obtained from the oscillation experiments. The accuracy of the experiments is discussed in the uncertainty analysis which is provided in Appendix C. The method used in developing the uncertainty analysis is given in Reference 7.

The values of the derivatives determined from the data in the appendix are given in Table 4. These derivatives are referred to the axes which have their origin 6.6042 feet (2.013 m) aft of the forward perpendicular (nose) on the hull centerline. The location of the reference point did not correspond with the longitudinal location of the center of buoyancy for any of the

configurations evaluated.

The values for the static derivatives were determined directly from the slopes at the origin of curves of force and moment coefficients versus angle of attack and drift. The angular velocity derivatives obtained from the oscillation experiments were obtained from the data using reduction equations in Reference 4. All derivatives with respect to angular quantities are given as "per radian."

For the vertical plane experiments, the forces X_S and Z_S acting on a control surface in the longitudinal and normal directions, respectively, (as defined by a coordinate system fixed in the control surface), are derived from the appropriate moments measured by the strain gages applied to the stock supporting the control surface as follows:

$$X_S = (M_1 - M_2)/b_1$$

$$Z_S = (M_3 - M_4)/b_2$$

where M_1 and M_3 are the moments measured at the inboard flexures, M_2 and M_4 are the moments measured at the outboard flexures, and b_1 and b_2 are the distances between the flexures for the X_S and Z_S forces, respectively.

The spanwise centers of pressure b_3 and b_4 from the centerline of the submarine for the X_S and Z_S forces, respectively, are determined as follows:

$$b_3 = [b_1 M_2/(M_1 - M_2)] + b_5$$

$$b_4 = [b_2 M_4/(M_3 - M_4)] + b_6$$

where b_5 and b_6 are the distances from the centerline of the submarine to the outer flexures for measuring the X_S and Z_S forces, respectively.

The chordwise center of pressure x_{CP} for the normal force can be determined as follows:

$$x_{CP} = -Q/Z_S$$

where Q is the hydrodynamic torque as measured by the instrumented stock.

It must be emphasized that the instrumented stock is rotated with the control surface. Whenever the control surface is deflected to some angle relative to the longitudinal axis of the hull, the normal and chordwise stock forces obtained are relative to the chord of the control surface and not the longitudinal axis of the hull. The normal and chordwise force components as measured by the instrumented stock can be resolved into normal and axial force components in the body frame of reference as follows:

$$X_{SB}' = X_S' \cos\delta_s + Z_S' \sin\delta_s$$

$$Z_{SB}' = Z_S'\cos\delta_s - X_S'\sin\delta_s$$

where X_{SB}' and Z_{SB}' are the axial force and normal force in the body frame of reference respectively.

The spanwise centers of pressure that are provided in Appendices A and B are calculated as a percentage of the mean span as measured from the root chord to the tip chord. The spanwise centers of pressure calculated from the strain gages which are used to determine the longitudinal forces are generally inaccurate since the longitudinal forces are relatively small. The spanwise centers of pressure for small angles of attack are also inaccurate because for these angles the normal forces are close to zero.

A similar analysis can be performed for the horizontal plane experiments.

Since the experiments were performed without a propulsor, it must be emphasized that the results of the experiments provide data for the contribution of the hull and appendages to the stability and control characteristics, but not for the contribution of the propulsor.

DISCUSSION OF RESULTS

The values of the hydrodynamic force and moment stability and control derivatives which are given in Table 4 are used in the submarine equations of motion to determine the dynamic stability of the vehicle. In addition, predictions of the motions of the submarine in six degrees-of-freedom can be made by using these equations of motion to perform computer simulations of various maneuvers as discussed in References 8 and 9.

The dynamic stability of the vehicle in the vertical plane at various ahead speeds can be analyzed on the basis of the nondimensional linearized equations of motion for the normal force and the pitching moment. When the equations are solved simultaneously using Laplace transforms the characteristic equation is a cubic.

If the symbol s is used for the Laplace transform operator, the characteristic equation is as follows:

$$\begin{aligned}
&[(Z_{\dot{w}}'-m')(M_{\dot{q}}'-I_y') - (Z_{\dot{q}}'+x_G'm'))(M_{\dot{w}}'+x_G'm')]s^3 \\
&+ [(Z_{\dot{w}}'-m')(M_q'-x_G'm') + Z_w'(M_{\dot{q}}'-I_y') \\
&- (Z_{\dot{q}}'+x_G'm')M_w' - (Z_q'+m')(M_{\dot{w}}'+x_G'm')]s^2 \\
&+ [Z_w'(M_q'-x_G'm') + (Z_{\dot{w}}'-m')M_\theta' - (Z_q'+m')M_w']s \\
&+ Z_w'M_\theta' = 0
\end{aligned}$$

The nondimensional roots of the characteristic equation will vary with speed due to the nondimensional hydrostatic metacentric moment derivative M_θ'. Hence, the resulting motion varies with speed, and is either oscillatory (underdamped) or aperiodic (overdamped). Dynamic stability is indicated if the signs of the roots of the characteristic stability equation are negative.

The characteristic equation reduces from a cubic to a quadratic in the Laplace transform operator if the metacentric derivative is zero. Since the metacentric derivative approaches zero as the ahead speed increases, an indication of the dynamic stability or instability at "infinite" speed is the positive or negative sign, respectively, of the constant term of the quadratic. If the submarine is dynamically stable at "infinite" speed, it will be dynamically stable at all ahead speeds, since the contribution of the metacentric derivative increases the dynamic stability.

The value of the margin of stability G_v in the vertical plane is calculated using the following equation as discussed in References 10 and 11:

$$G_v = 1 - M_w'(Z_q' + m')/[Z_w'(M_q' - x_G'm')]$$

The margin of stability is constructed from the components of the constant term of the quadratic equation. Basically, it is a measure of how much, and in what direction, the constant term is different from zero. If the value of G_v is greater than zero, the vehicle is dynamically stable. If the value is less than zero, the vehicle is unstable. The magnitude of the margin of stability index indicates the degree of dynamic stability. A value of about 1.0 indicates that the vehicle has a very high degree of stability, while a value only slightly greater than zero would indicate marginal stability. Generally, a submarine with a very high degree of stability in the vertical planes does not respond adequately to a sternplane deflection.

The characteristic equation of motion for the horizontal plane is a quadratic equation since there is no metacentric moment derivative as follows:

$$[(Y_{\dot v}'-m')(N_{\dot r}'-I_z') - (Y_{\dot r}'-x_Gm')(N_{\dot v}'-x_G'm')]s^2$$

$$+ [(Y_{\dot v}'-m')(N_r-x_G'm') + Y_v'(N_{\dot r}'-I_z')$$

$$- (Y_{\dot r}'-x_G'm')N_v' - (Y_r'-m')(N_{\dot v}'-x_G'm')]s$$

$$+ Y_v'(N_r'-x_G'm') - (Y_r'-m')N_v' = 0$$

Therefore, the resulting motion is aperiodic at all speeds. Analogous to G_v, the equation for G_h is as follows:

$$G_h = 1 - N_v'(Y_r' - m')/[Y_v'(N_r'-x_G'm')]$$

The value of G_v shown in Table 3 is -1.16 which indicates that the submarine is unstable in the vertical plane. This is due to the relatively small planform

area and outreach of the sternplanes. The values of G_h shown in Table 4 are all negative which indicates that the submarine is unstable in the horizontal plane as well. For example, the value is -0.44 for the fully appended submarine (Configuration 2). The uncertainty in the value of G_h can be determined by using the method described in Appendix C and Reference 7. Assuming that the uncertainty in the static stability and rotary derivatives is 5 and 10 percent, respectively, the uncertainty in G_h is 43 percent. Hence, the value of G_h could be between -0.63 and -0.25 for Configuration 2.

CONCLUSIONS

A program of straightline captive-model experiments was performed in the vertical and horizontal planes of motion at deep submergence to investigate the stability and control characteristics of the DARPA SUBOFF model. Based on the results of the experiments, the following conclusions can be drawn:

1. The fully appended submarine design is unstable in the vertical plane of motion.

2. The fully appended submarine design is unstable in the horizontal plane of motion.

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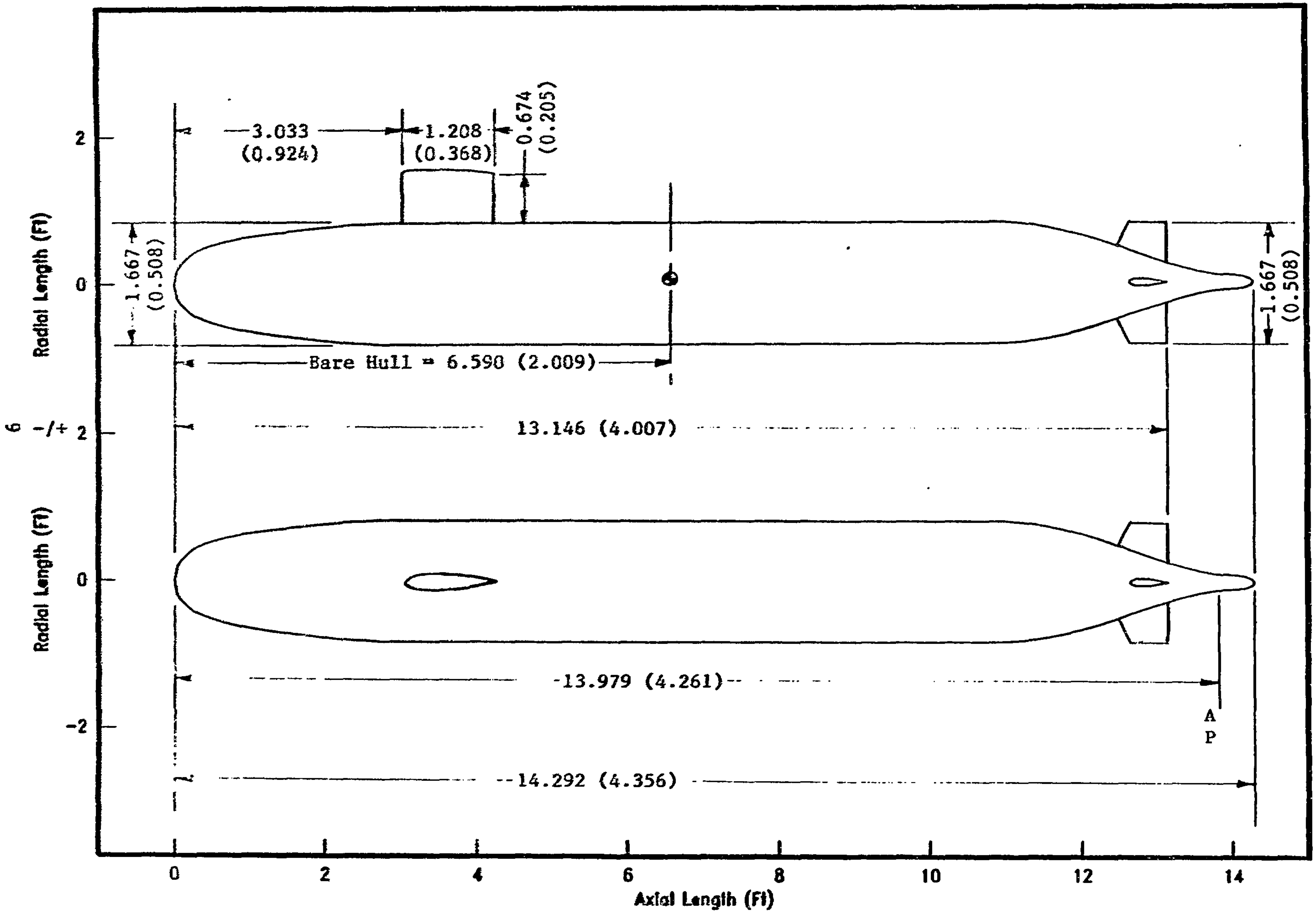

Fig. 1. Drawing of the DARPA SUBOFF model.

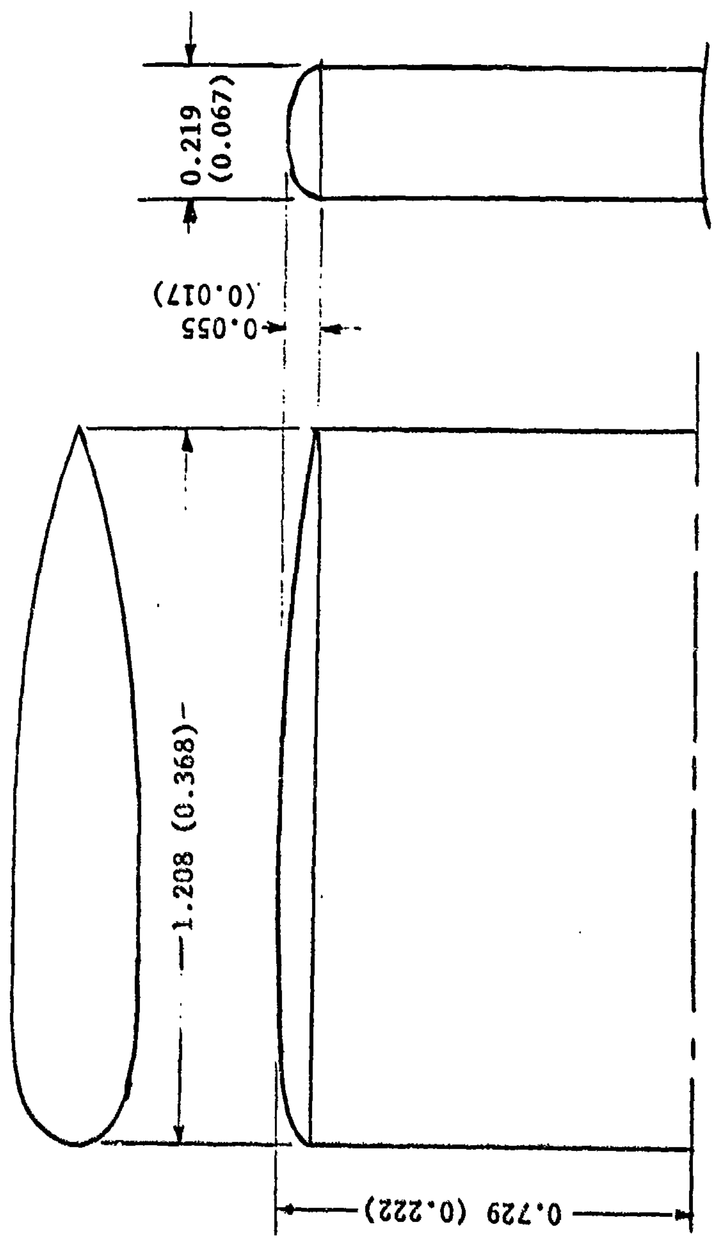

Fig. 2. Drawing of the sail.

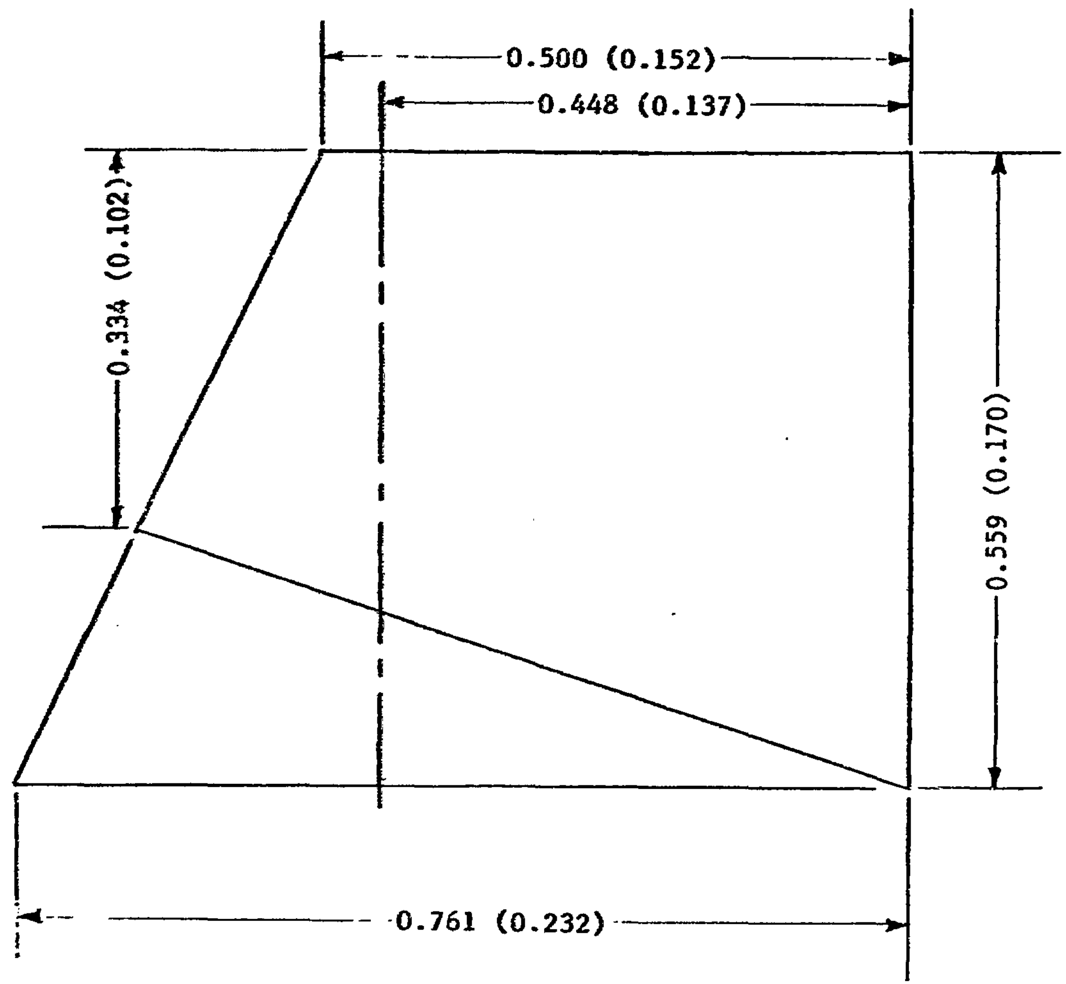

Fig. 3. Drawing of the stern appendages.

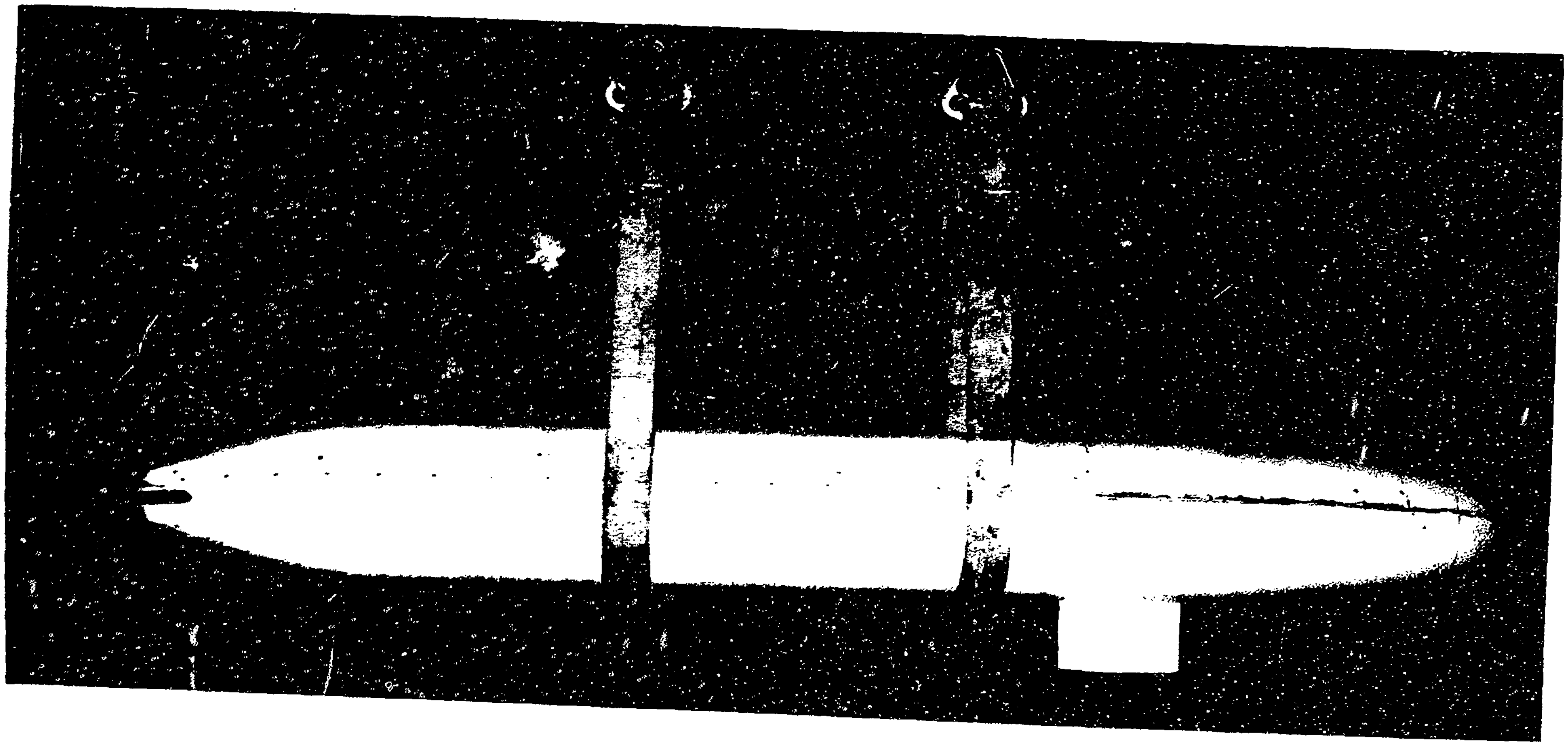

Fig. 4. Photograph of DTRC Model 5470.

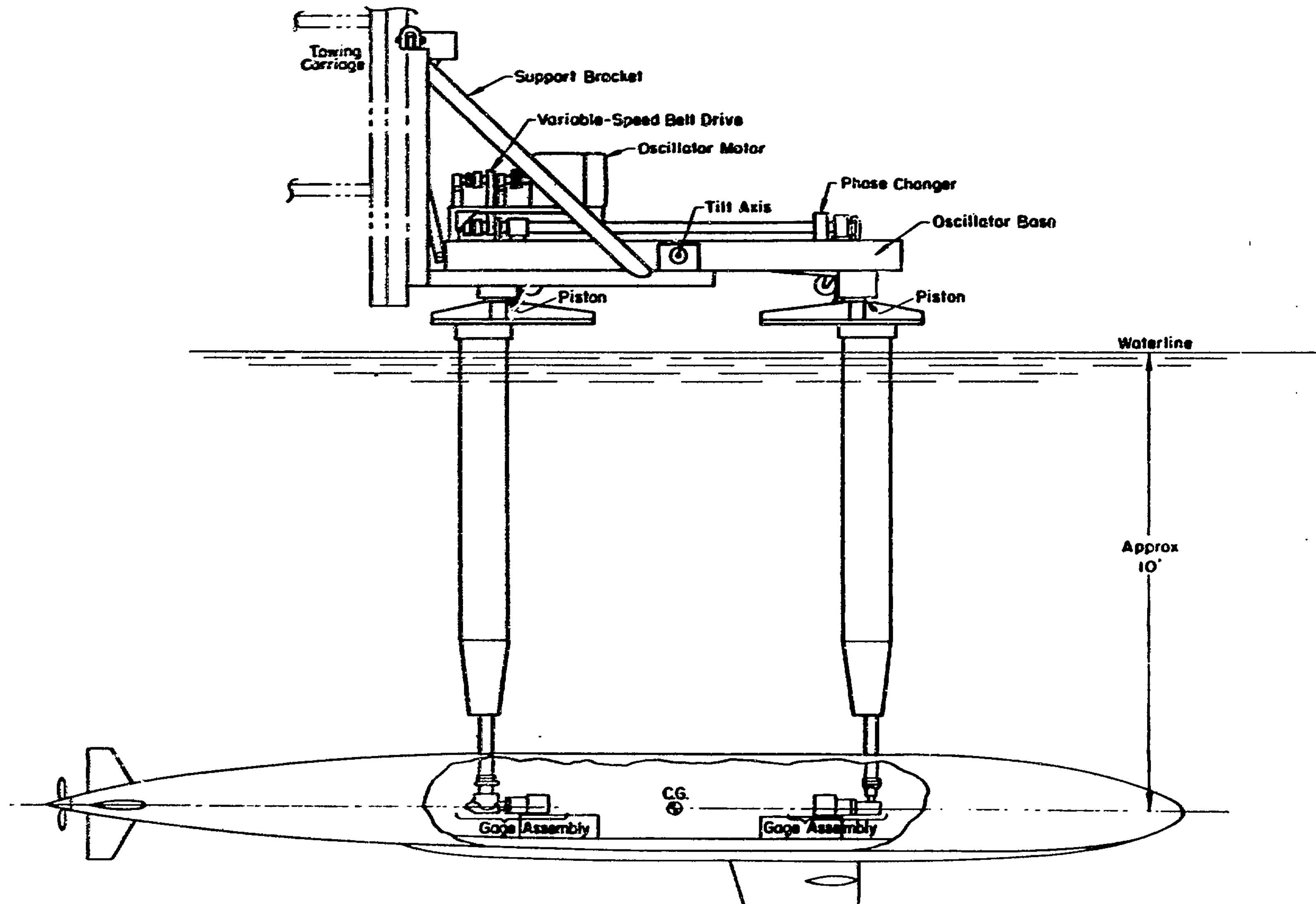

Fig. 5. Sketch of the DTRC Planar Motion Mechanism with a model attached.

Table 1. Geometric characteristics of the DARPA SUBOFF model.

DESIGN PARAMETERS - HULL

Length Between Perpediculars	(LCP)	(ft)	13.9792
Length Overall	(LOA)	(ft)	14.2917
Length to the Center of Buoyancy	(LCB)	(ft)	6.6042
Length of Forebody	(L_F)	(ft)	3.3333
Length of Parallel Middlebody	(L_P)	(ft)	7.3125
Length of Run	(L_R)	(ft)	3.6458
Diameter		(ft)	1.6667
Fineness Ratio			8.575

CALCULATED AND ESTIMATED PARAMETERS
Vertical Plane

Item	Config 1 Fully Appended
VOL(ft^3)	24.9899
LCB(ft)	6.6139
VCB(ft)	-0.006669
WS(ft^2)	67.651
Buoyancy(lb)	1556.2363
m'	0.018296
x_G'm'*10^4	-0.127467
I_z'	0.001084

CALCULATED AND ESTIMATED PARAMETERS
Horizontal Plane

Item	Config 3 Bare Hull	Config 4 B.H. + Sail	Config 5 B.H. + 4 Planes	Config 6 B.H. + Ring Wing 1	Config 2 Fully Appended
VOL(ft^3)	24.692	24.83434	24.78279	24.75678	24.98991
LCB(ft)	6.59003	6.5726	6.612732	6.60889	6.613906
VCB(ft)	0.0	-0.006711	0.0	0.0	-0.006669
WS(ft^2)	63.717	65.854	65.514	63.717	67.651
Buoyancy(lb)	1537.6841	1546.5483	1543.3380	1541.7183	1556.2363
m'	0.018078	0.018182	0.018144	0.018123	0.018296
x_G'm'*10^4	0.388697	0.410569	-0.111173	-0.061235	-0.127467
I_y'	0.001053	0.001059	0.001066	0.001066	0.001084

NOTES: 1 - meters = feet * 0.3048 kilograms = pounds * 2.2046
2 - Wetted Surface of Ring Wing and Its Supports are Assummed = 0.00

Table 1. (Continued)

DESIGN PARAMETERS - SAIL

Span	(ft)	0.729
Root Chord	(ft)	1.208
Tip Chord	(ft)	1.208
FP to Sail LE Distance	(ft)	3.033
Aspect Ratio		0.603

CALCULATED PARAMETER - SAIL

Planform Area	(ft^2)	0.855

DESIGN PARAMETERS - CONTROL PLANE

Span	(ft)	0.438
Root Chord	(ft)	0.704
Tip Chord	(ft)	0.500
FP to Plane TE Distance	(ft)	13.146
Aspect Ratio		0.720
Section Profile (NACA)		0020

CALCULATED PARAMETER - CONTROL PLANE

Planform Area	(ft^2)	0.267

Table 2. Nondimensional offsets and cross sectional areas for the hull.

STATION	B/B_X	A/A_X
0.0	0.00000	0.00000
0.1	0.29058	0.08444
0.2	0.39396	0.15520
0.3	0.46600	0.21715
0.4	0.52147	0.27194
0.5	0.56627	0.32066
0.6	0.60352	0.36424
0.7	0.63514	0.40340
1.0	0.70744	0.50047
2.0	0.84713	0.71763
3.0	0.94066	0.88484
4.0	0.99282	0.98570
7.7143	1.00000	1.00000
10.0	1.00000	1.00000
15.1429	1.00000	1.00000
16.0	0.97598	0.95253
17.0	0.81910	0.67093
18.0	0.55025	0.30278
19.0	0.26835	0.07201
20.0	0.11724	0.01375
20.1	0.11243	0.01264
20.2	0.10074	0.01015
20.3	0.07920	0.00628
20.4	0.03178	0.00101
20.4167	0.00000	0.00000

Table 3. Schedule of the stability and control experiments.

CONFIGURATION 1 - VERTICAL PLANE, FULLY APPENDED WITH RING WING NO. 1

Type of Test	Angles of Attack (deg)	Stern Plane Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	0	6.5	
Sternplane Variation	+/- 4	+/- 15	6.5	
Heaving	0	0	0.0	1.112 & 2.220
Pitching	0	0	0.0	1.112 & 2.220
Pitching	0	0	4.5,5.0, 6.0,6.5	2.220

CONFIGURATION 2 - HORIZONTAL PLANE, FULLY APPENDED WITH RING WING NO. 1

Type of Test	Angles of Drift (deg)	Rudder Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	0	6.5	
Rudder Variation	+/- 4	+/- 15	6.5	
Swaying	0	0	0.0	1.112 & 2.220
Yawing	0	0	0.0	1.112 & 2.220
Yawing	0	0	4.5,5.0, 6.0,6.5	2.220

CONFIGURATION 3 - HORIZONTAL PLANE, BARE HULL

Type of Test	Angles of Drift (deg)	Rudder Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	NA	6.5	
Swaying	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	4.5,5.0, 6.0,6.5	2.220

Table 3. (Continued)

CONFIGURATION 4 - HORIZONTAL PLANE, HULL AND SAIL ONLY

Type of Test	Angles of Drift (deg)	Rudder Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	NA	6.5	
Swaying	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	4.5,5.0, 6.0,6.5	2.220

CONFIGURATION 5 - HORIZONTAL PLANE, HULL AND CONTROL SURFACES ONLY

Type of Test	Angles of Drift (deg)	Rudder Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	0	6.5	
Swaying	0	0	0.0	1.112 & 2.220
Yawing	0	0	0.0	1.112 & 2.220
Yawing	0	0	4.5,5.0, 6.0,6.5	2.220

CONFIGURATION 6 - HORIZONTAL PLANE, HULL AND RING WING NO.1 ONLY

Type of Test	Angles of Drift (deg)	Rudder Angles (deg)	Model Speeds (knots)	Omega (rad/sec)
Static Stability	+/- 18	NA	6.5	
Swaying	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	0.0	1.112 & 2.220
Yawing	0	NA	4.5,5.0, 6.0,6.5	2.220

Table 4. Nondimensional stability and control derivatives.

Vertical Plane

Item	Config 1 Fully Appended
Z_w'	-0.013910
M_w'	0.010324
Z_q'	-0.007545
M_q'	-0.003702
$Z_{\dot{w}}'$	-0.014529
$M_{\dot{w}}'$	-0.000561
$Z_{\dot{q}}'$	-0.000633
$M_{\dot{q}}'$	-0.000860
G	-1.162874
$Z_{\delta s}'$	-0.005603
$M_{\delta s}'$	-0.002409

Horizontal Plane

Item	Config 3 Bare Hull	Config 4 B.H. + Sail	Config 5 B.H. + 4 Planes	Config 6 B.H. + Ring Wing 1	Config 2 Fully Appended
Y_v'	-0.005948	-0.023008	-0.010494	-0.005943	-0.027834
N_v'	-0.012795	-0.015534	-0.011254	-0.012939	-0.013648
K_v'	-0.000019	-0.000697	-0.000033	-0.000019	-0.000584
Y_r'	0.001811	-0.000023	0.006324	0.003811	0.005251
N_r'	-0.001597	-0.002378	-0.003064	-0.002325	-0.004444
$Y_{\dot{v}}'$	-0.013270	-0.015042	-0.014711	-0.014899	-0.016186
$N_{\dot{v}}'$	0.000202	0.000008	0.000415	0.000625	0.000396
$Y_{\dot{r}}'$	0.000060	-0.000196	0.000465	0.000347	0.000398
$N_{\dot{r}}'$	-0.000676	-0.000710	-0.000744	-0.000787	-0.000897
G	-20.38506	-4.081818	-3.152048	-12.43748	-0.443297
$Y_{\delta r}'$					0.005929
$N_{\delta r}'$					-0.002217
$K_{\delta r}'$					-0.000005

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APPENDIX A

RESULTS OF THE CAPTIVE-MODEL EXPERIMENTS IN GRAPHICAL FORM

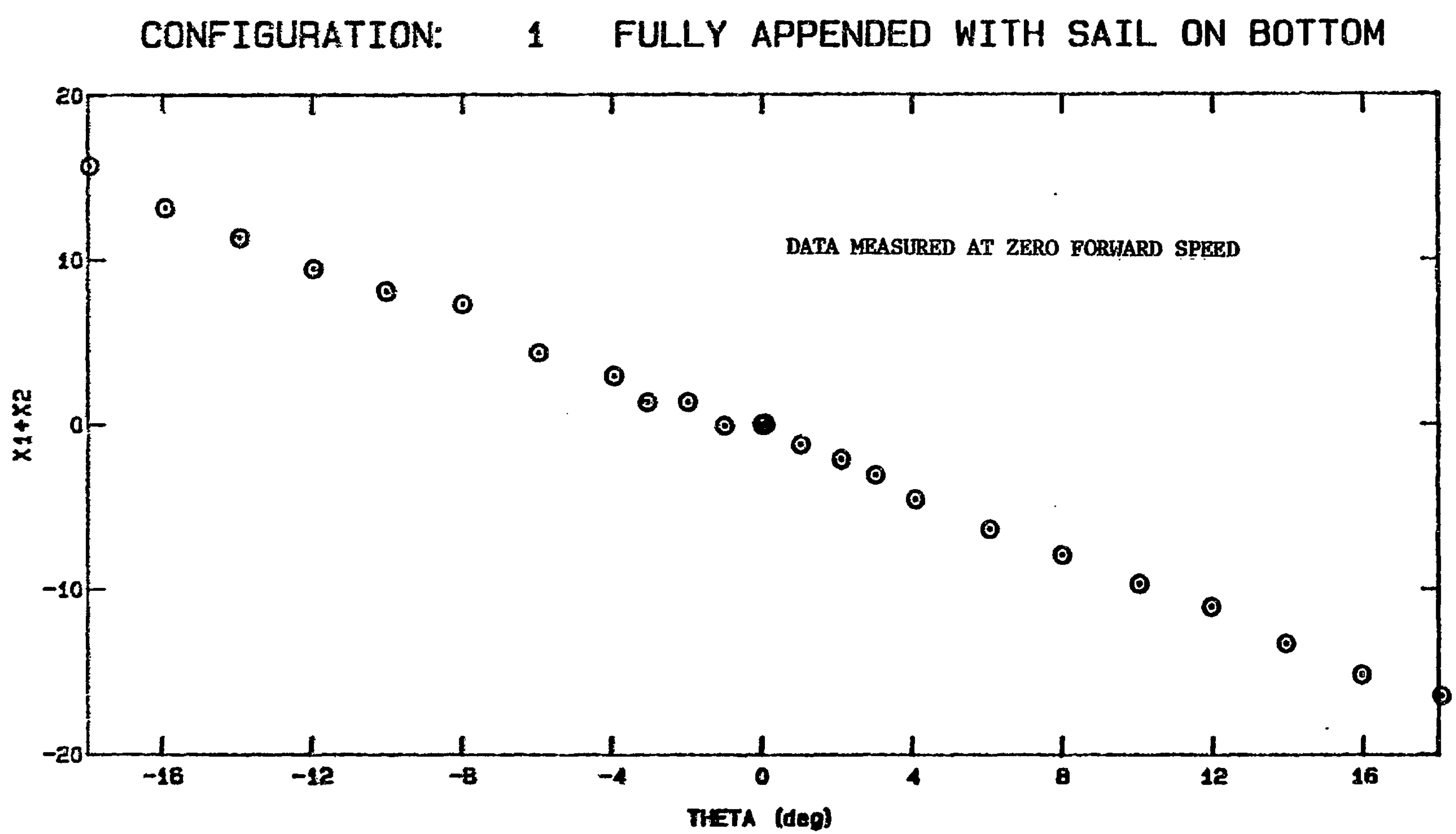

Fig. 6. Effect of tilt table angle on the longitudinal force at standstill for use in correcting the underway longitudinal force data and in determining the weight of the model in water for Configuration 1.

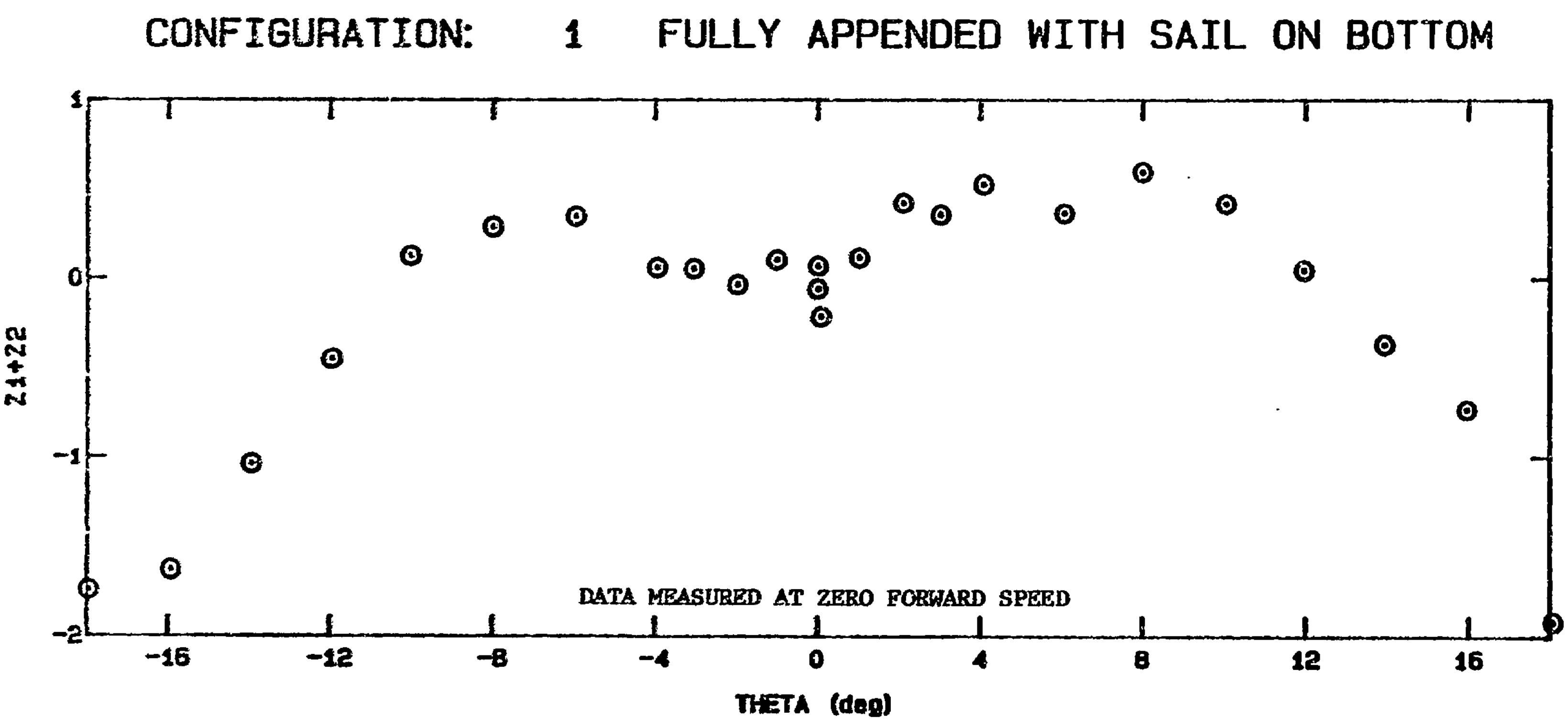

Fig. 7. Effect of tilt table angle on the normal force at standstill for use in correcting the underway normal force data for Configuration 1.

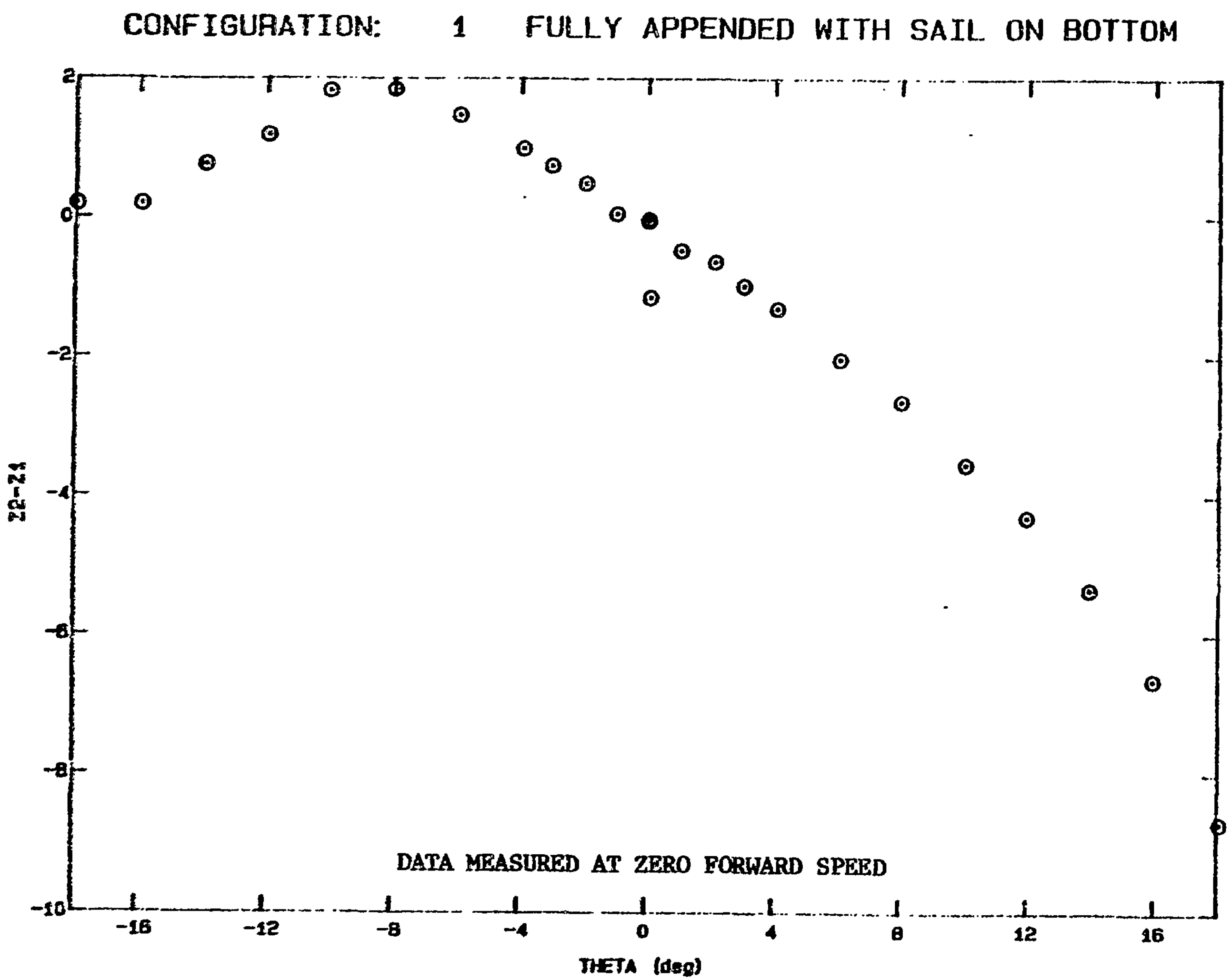

Fig. 8. Effect of tilt table angle on the difference between the forward and aft normal force data for use in correcting the underway pitching moment data and in determining the longitudinal location of the center of gravity for Configuration 1.

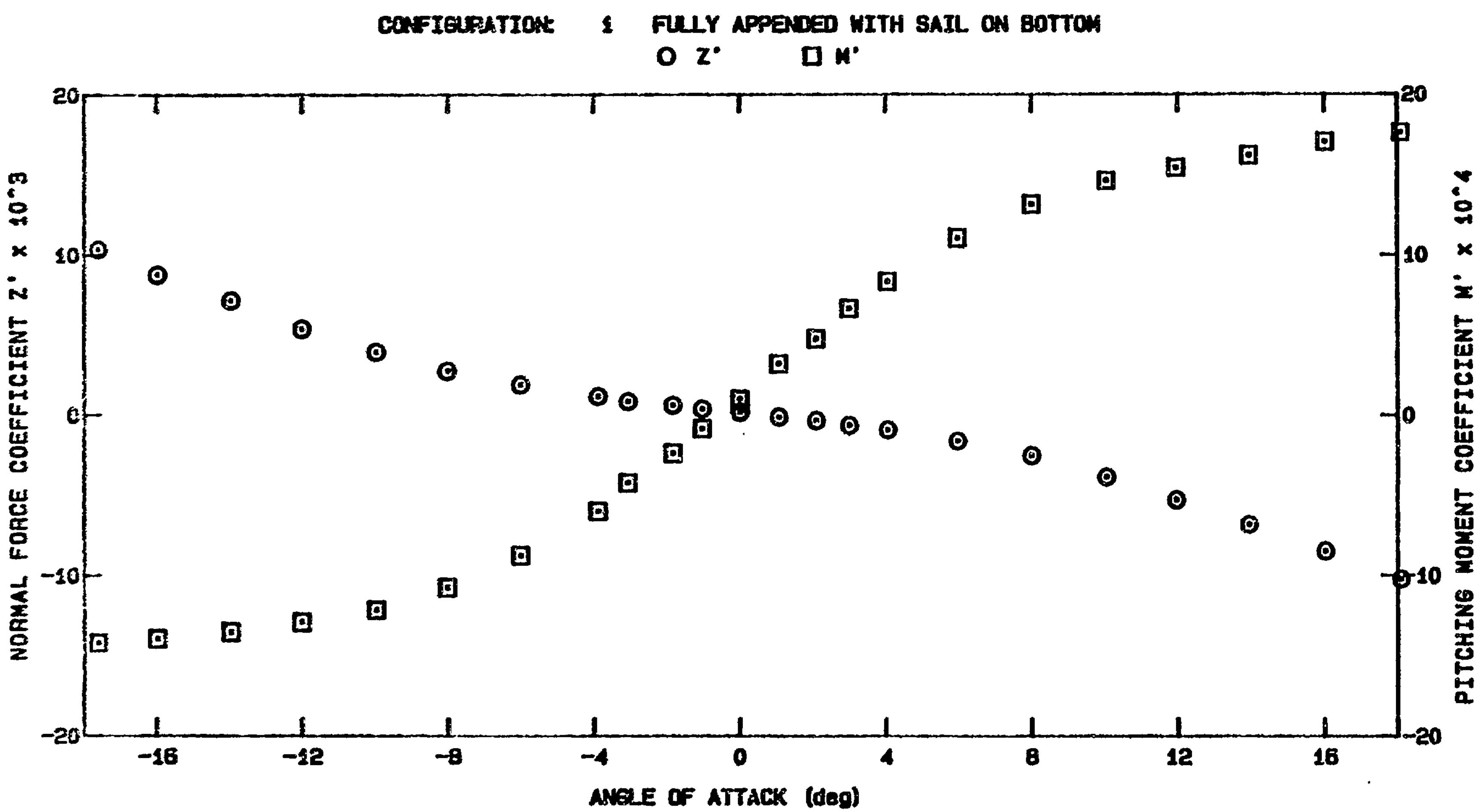

Fig. 9. Effect of angle of attack on the normal force and pitching moment coefficients for Configuration 1.

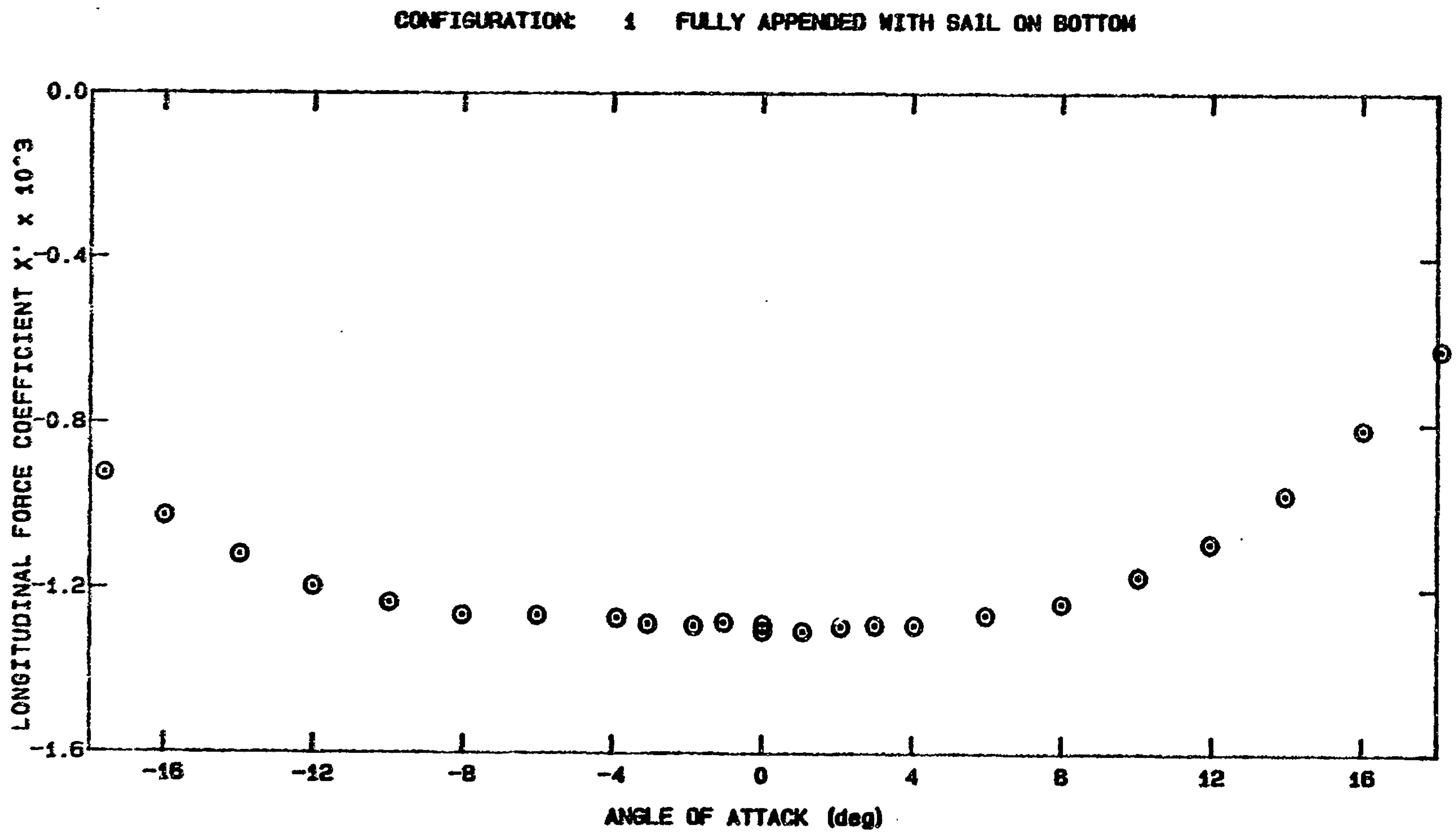

Fig. 10. Effect of angle of attack on the longitudinal force coefficient for Configurations 1.

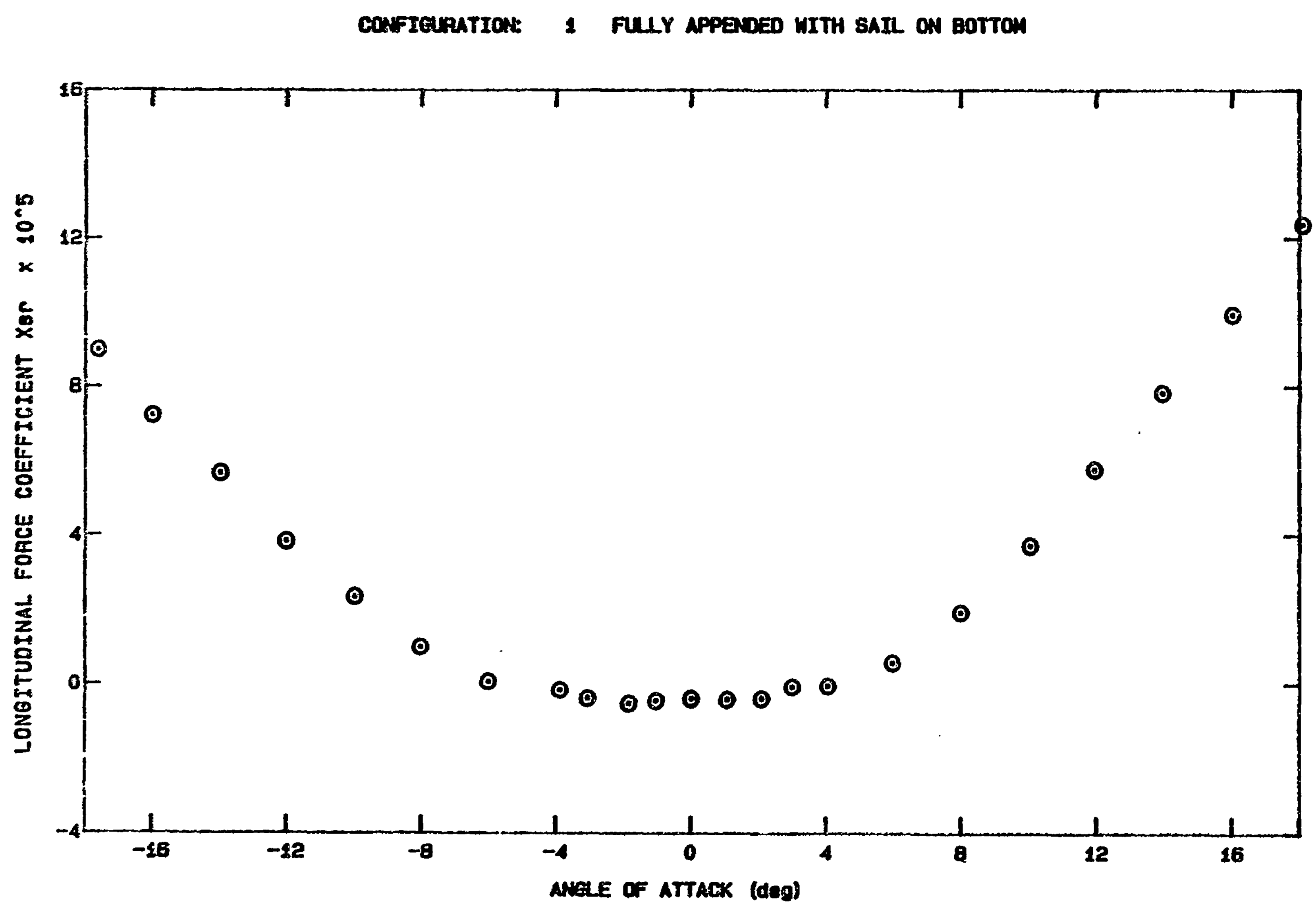

Fig. 11. Effect of angle of attack on the longitudinal force coefficient measured on one sternplane for Configuration 1.

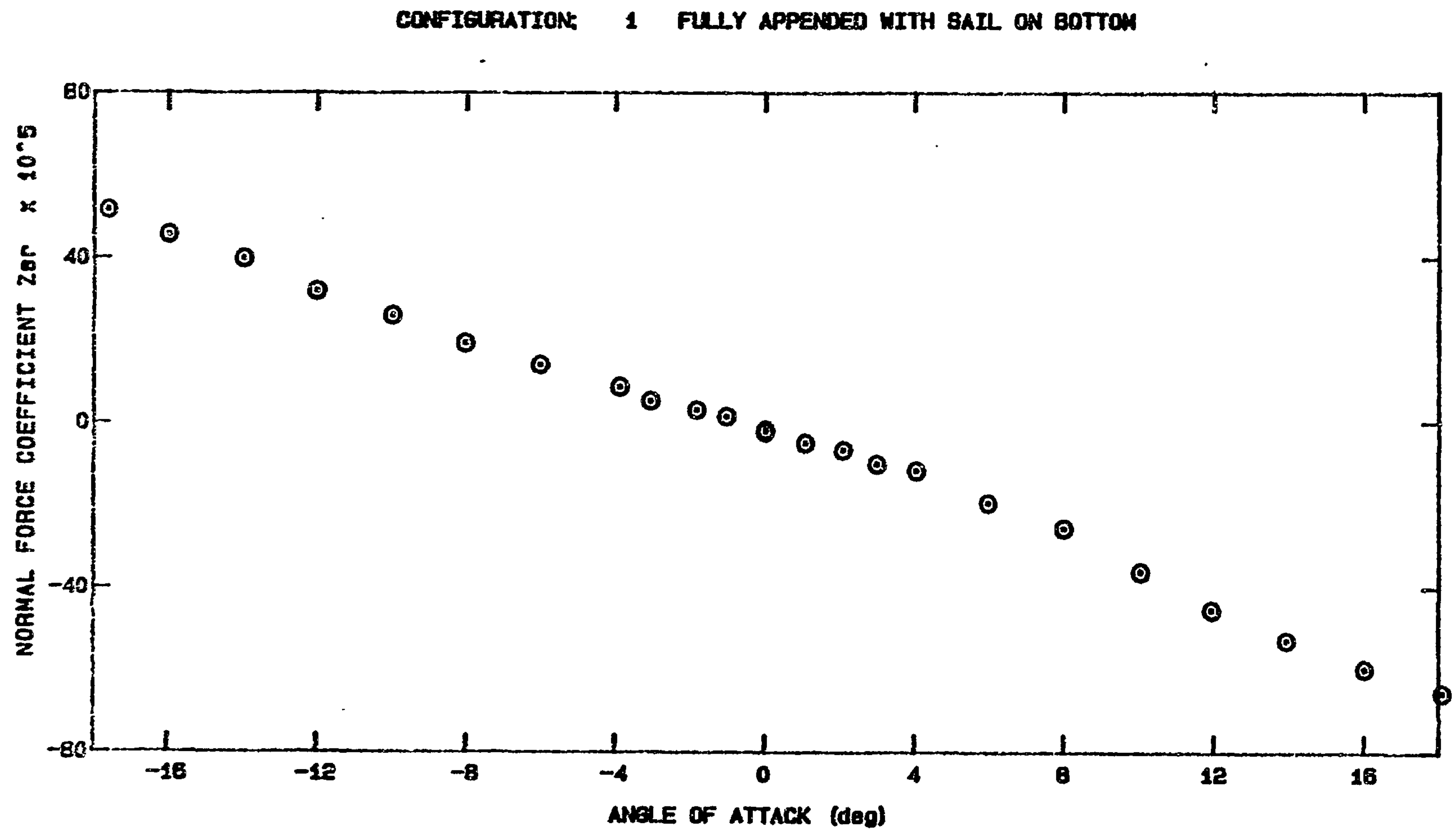

Fig. 12. Effect of angle of attack on the normal force coefficient measured on one sternplane for Configuration 1.

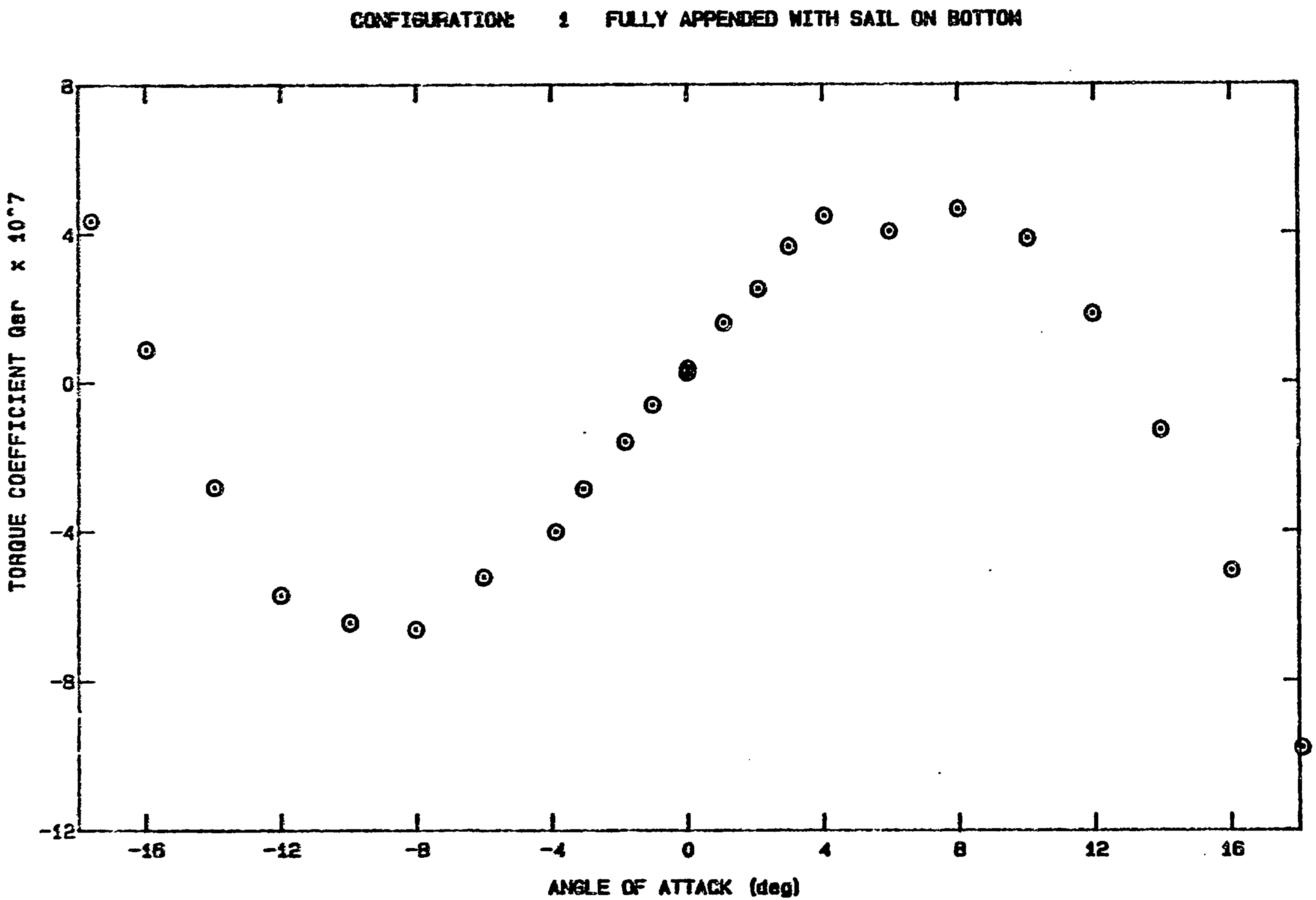

Fig. 13. Effect of angle of attack on the hydrodynamic torque coefficient measured on the stock of one sternplane for Configuration 1.

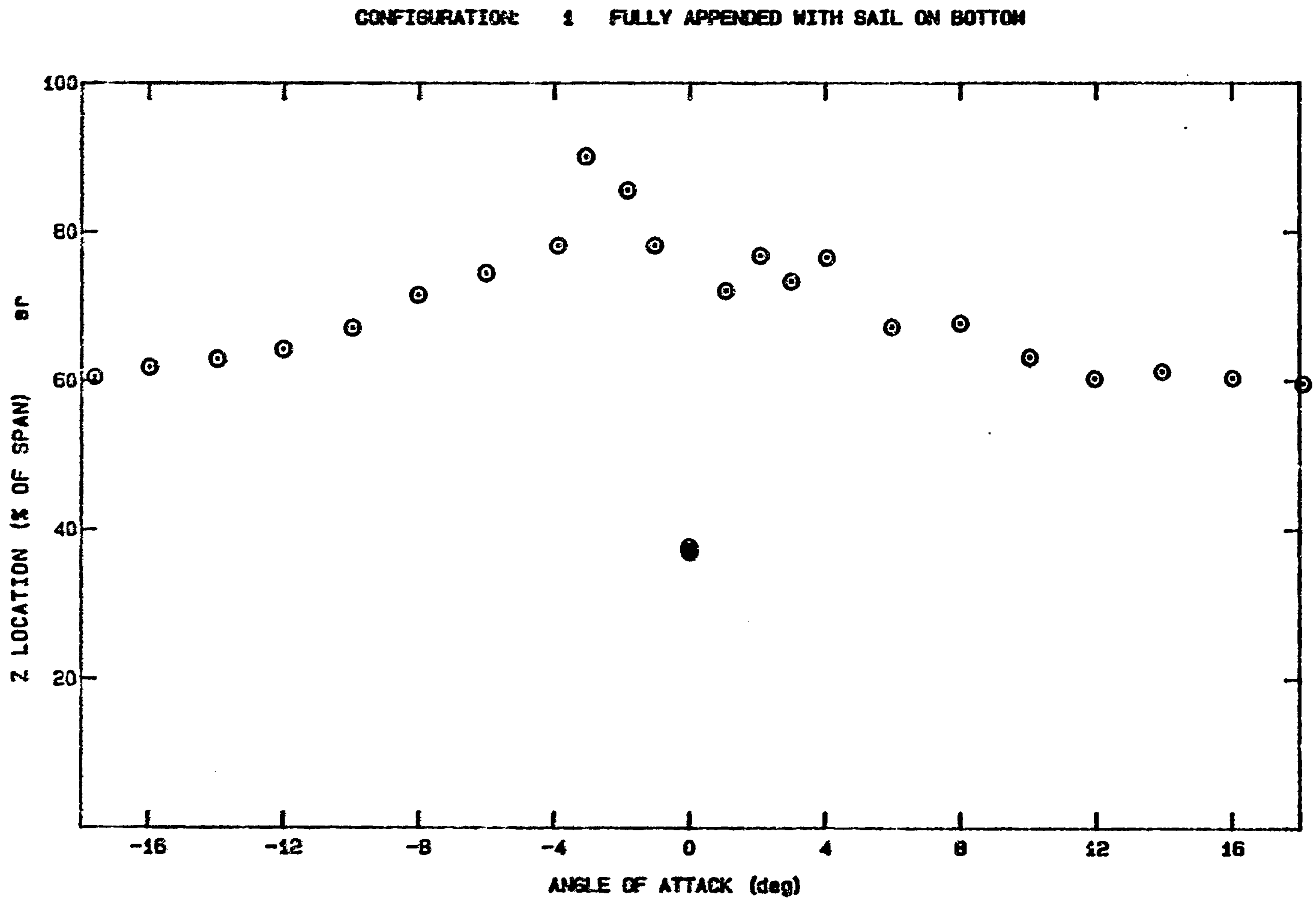

Fig. 14. Effect of angle of attack on the percent spanwise location of the center of pressure measured on one sternplane for Configuration 1.

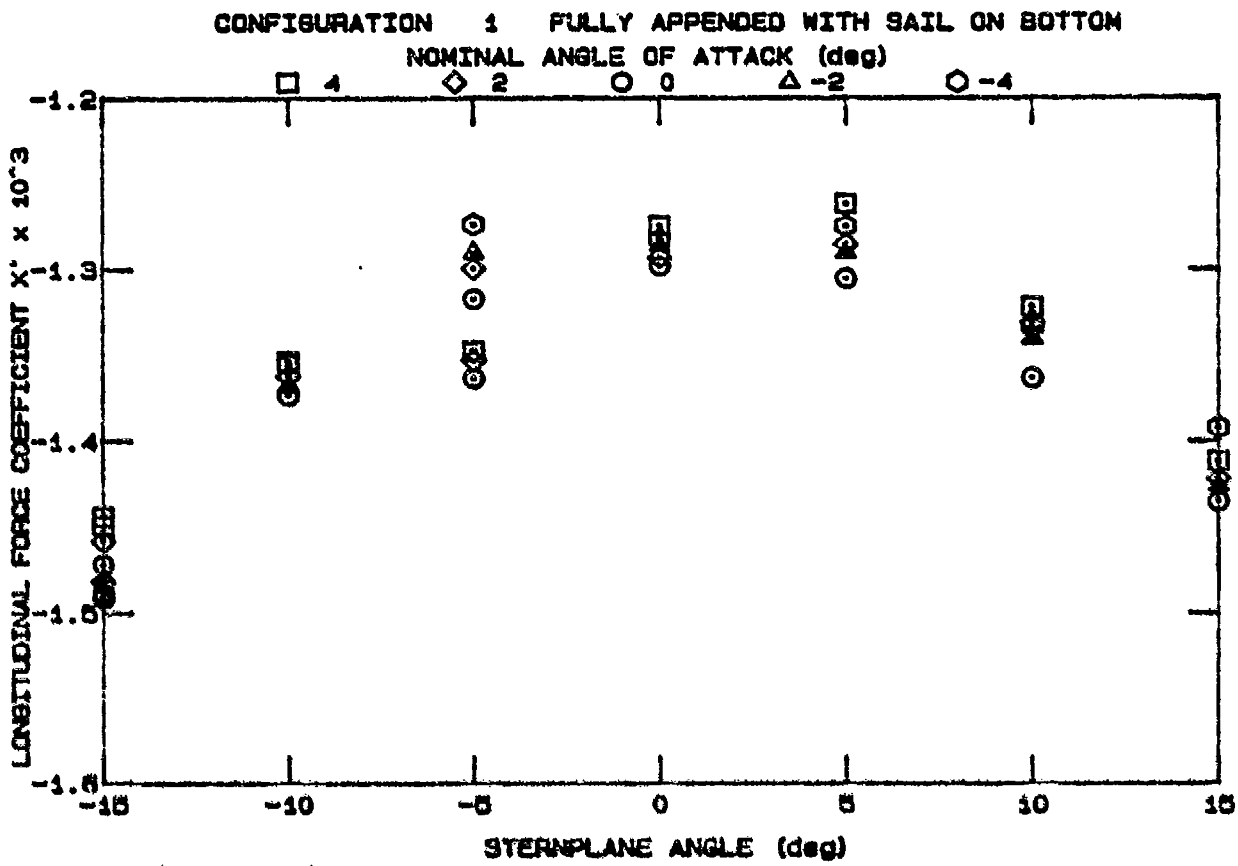

Fig. 15. Effect of sternplane angle on the longitudinal force coefficient for various angles of attack for Configuration 1.

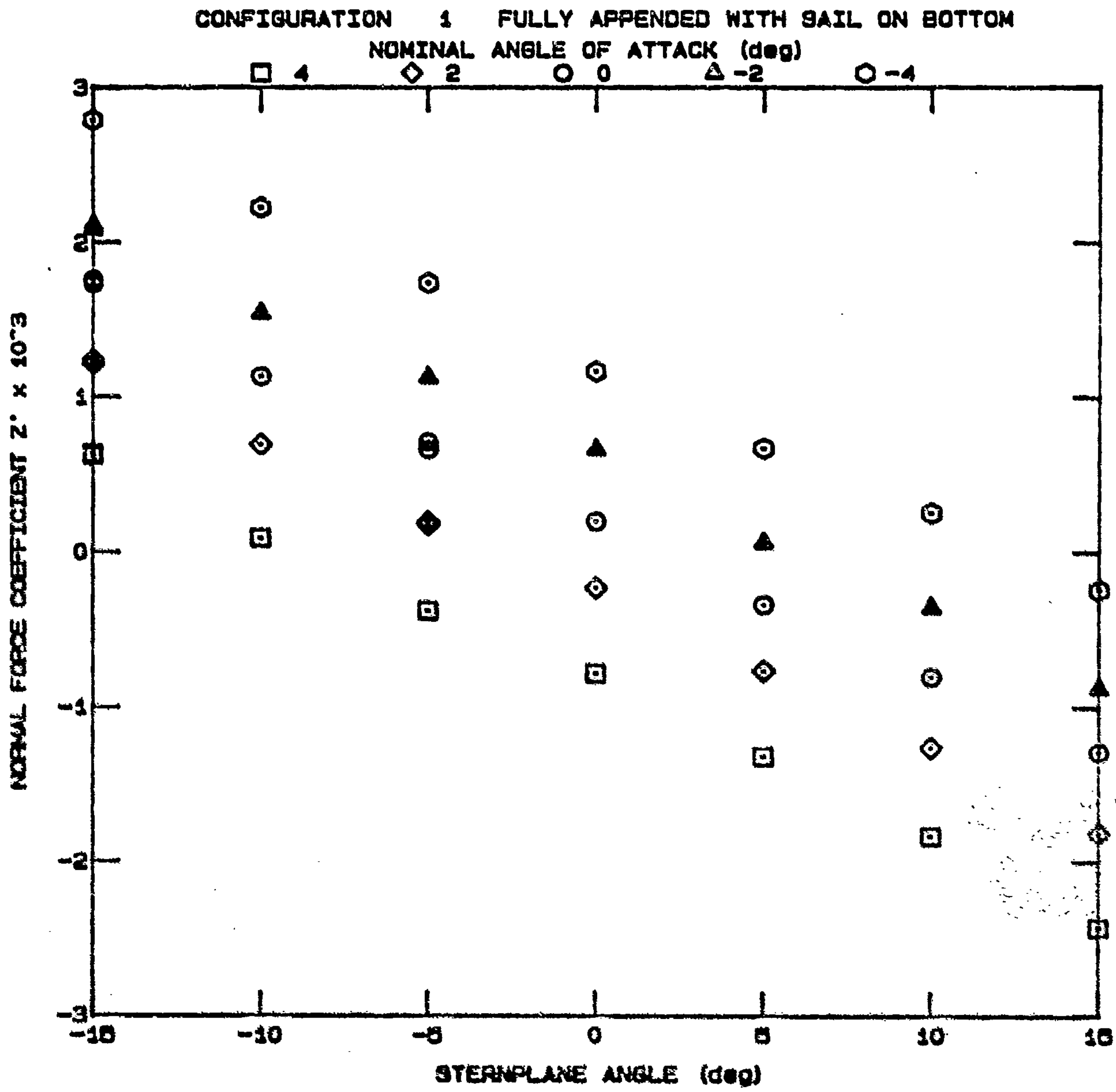

Fig. 16. Effect of sternplane angle on the normal force coefficient for various angles of attack for Configuration 1.

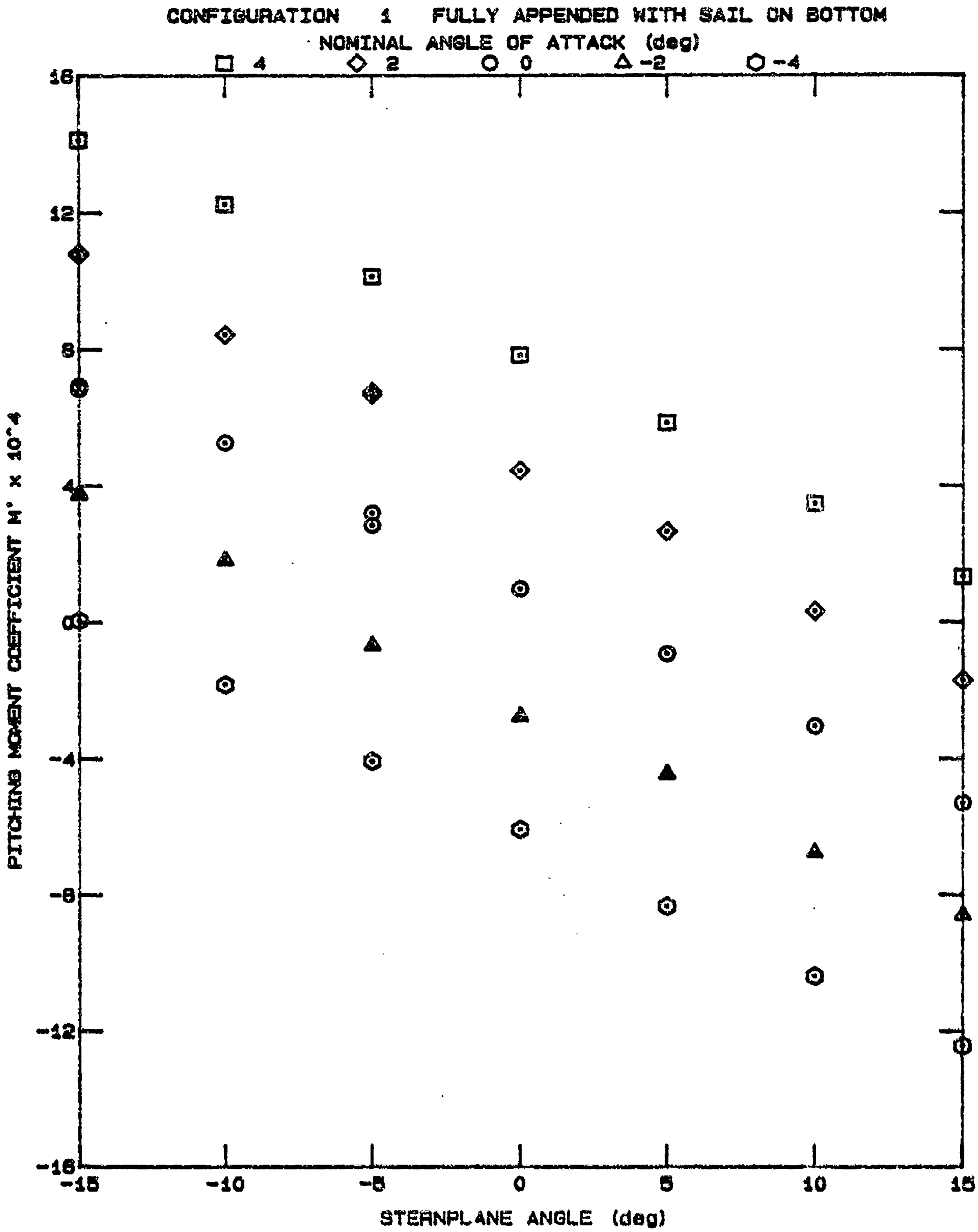

Fig. 17. Effect of sternplane angle on the pitching moment coefficient for various angles of attack for Configuration 1.

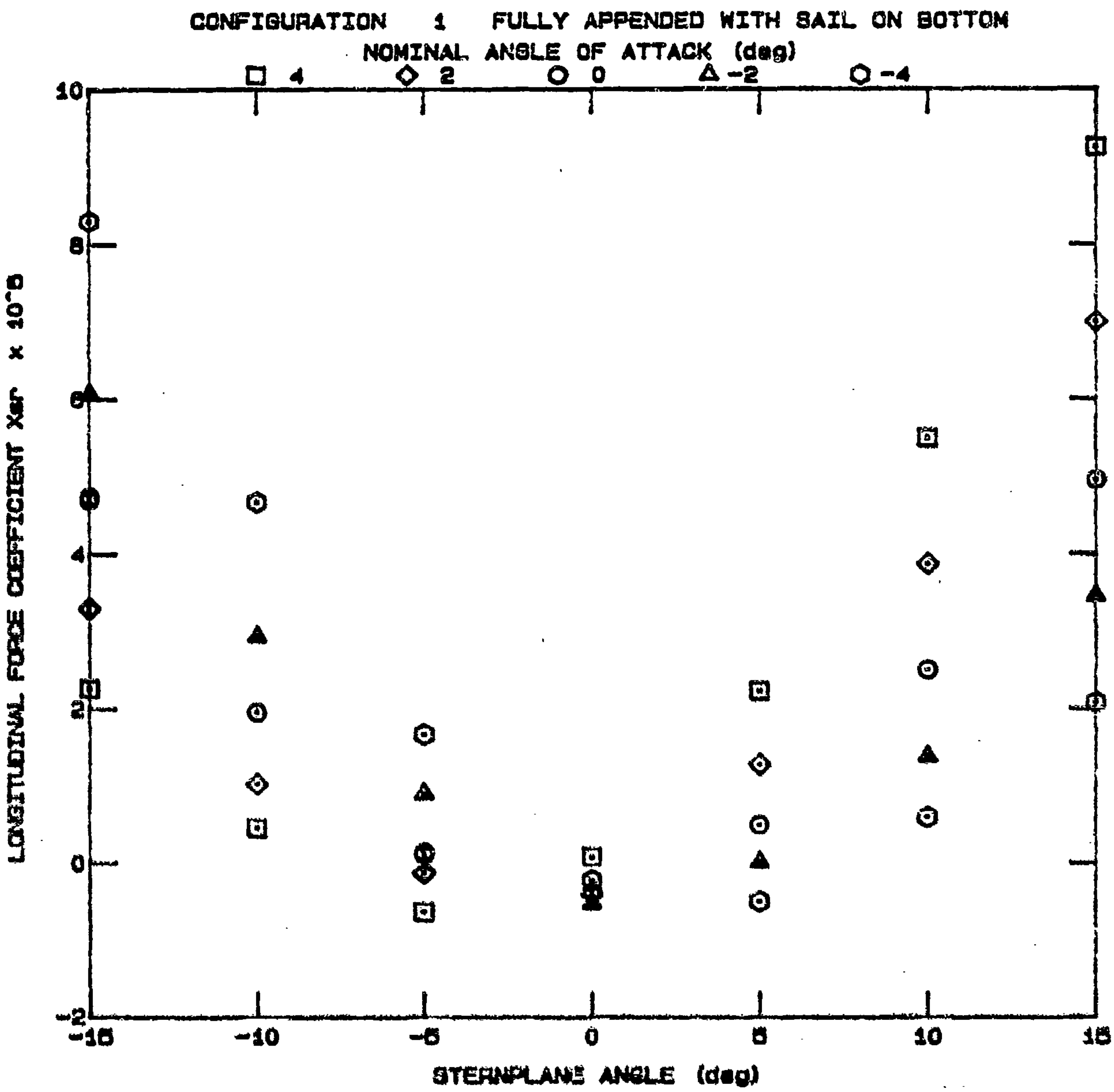

Fig. 18. Effect of sternplane angle on the longitudinal force coefficient measured on one sternplane for Configuration 1.

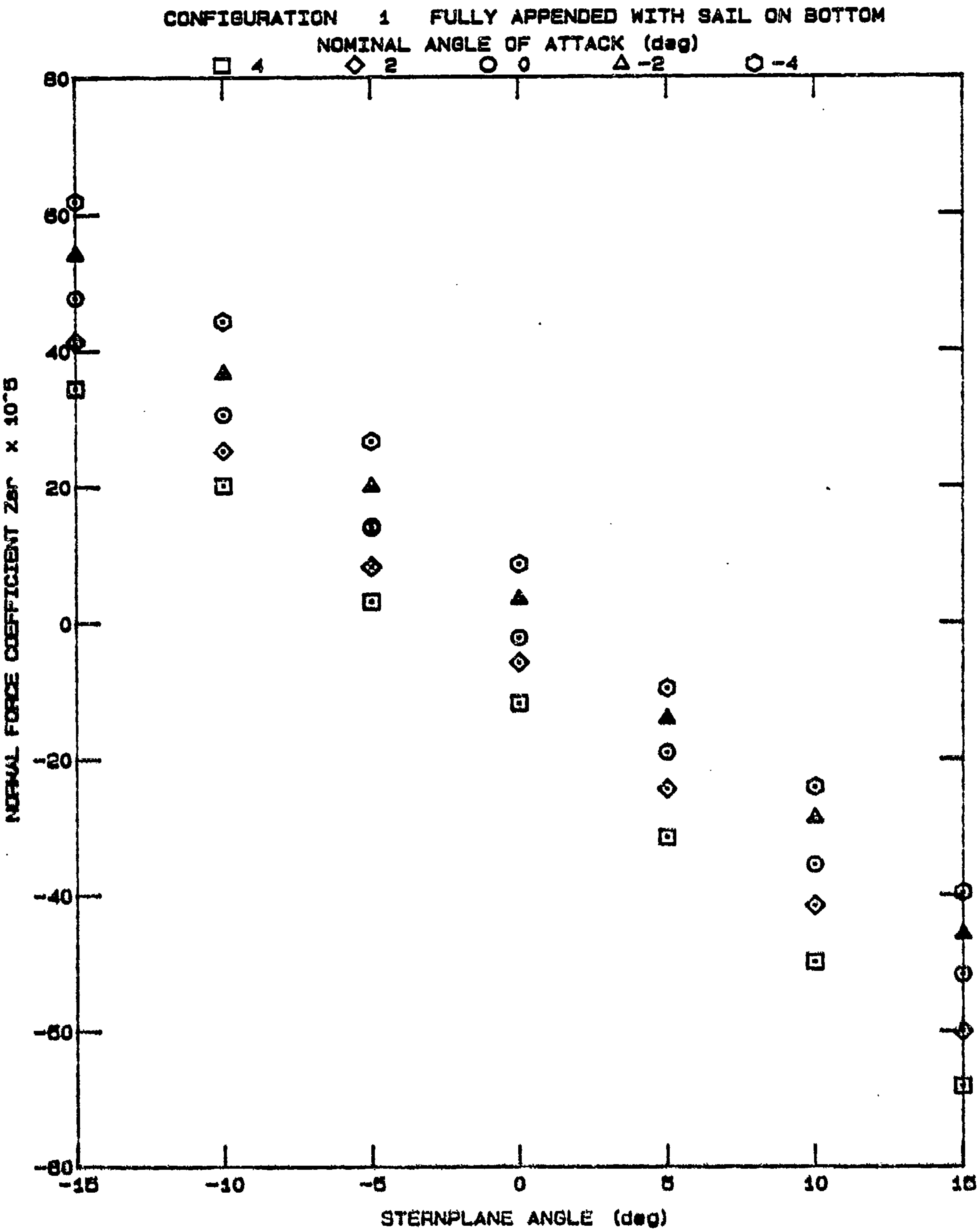

Fig. 19. Effect of sternplane angle on the normal force coefficient measured on one sternplane for Configuration 1.

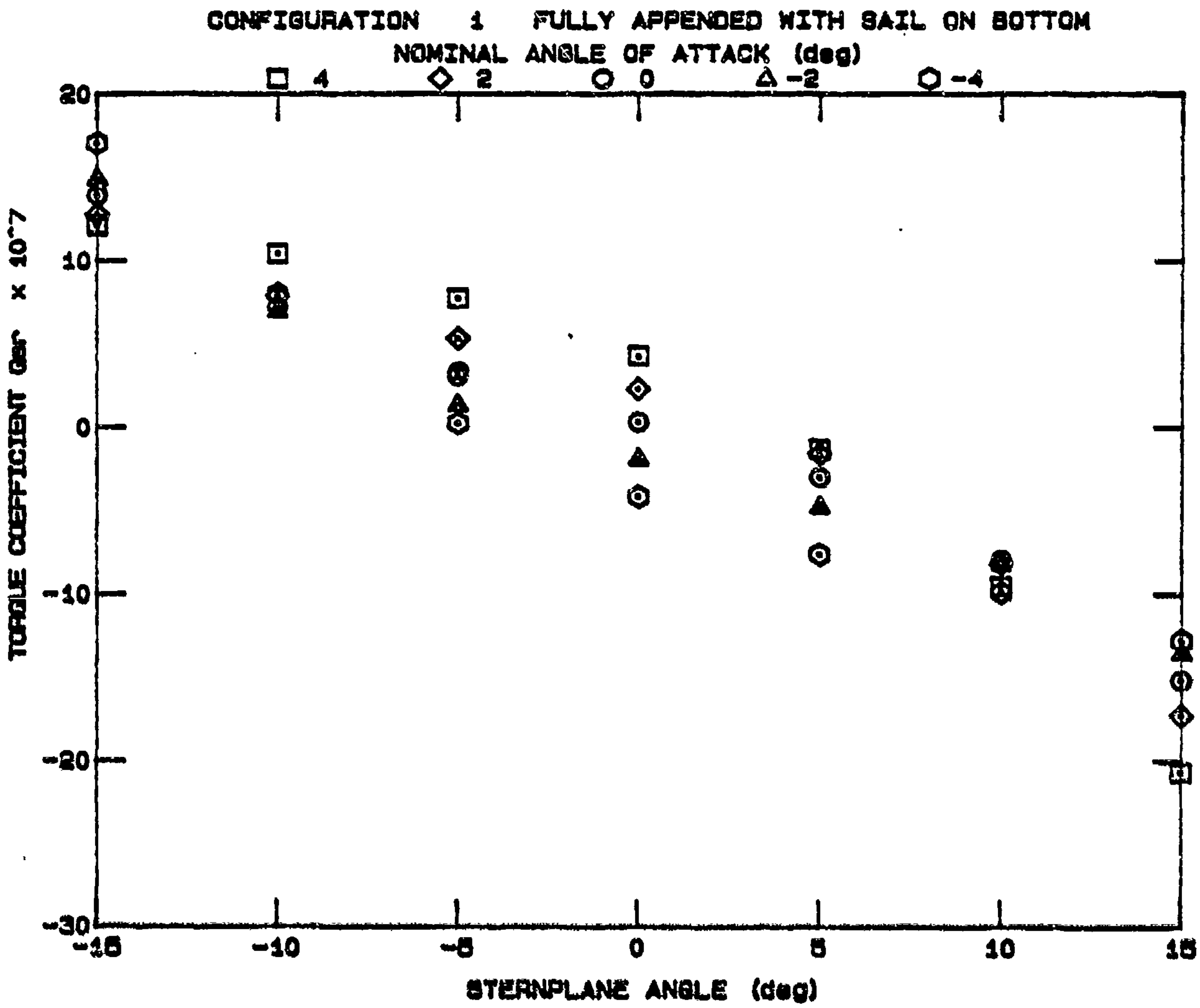

Fig. 20. Effect of sternplane angle on the hydrodynamic torque coefficient measured on the stock of one sternplane for Configuration 1.

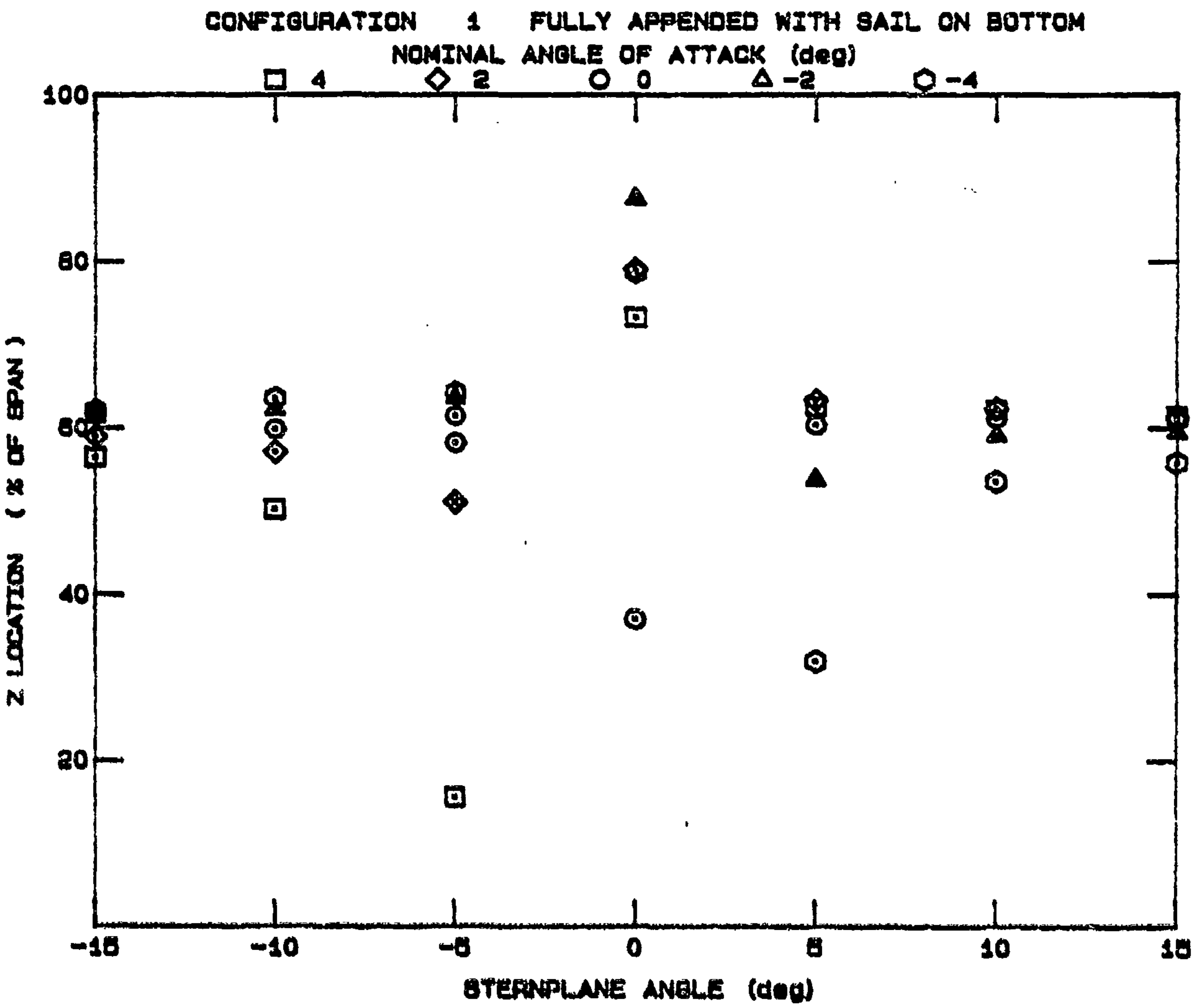

Fig. 21. Effect of sternplane angle on the percent spanwise location of the center of pressure measured on one sternplane for Configuration 1.

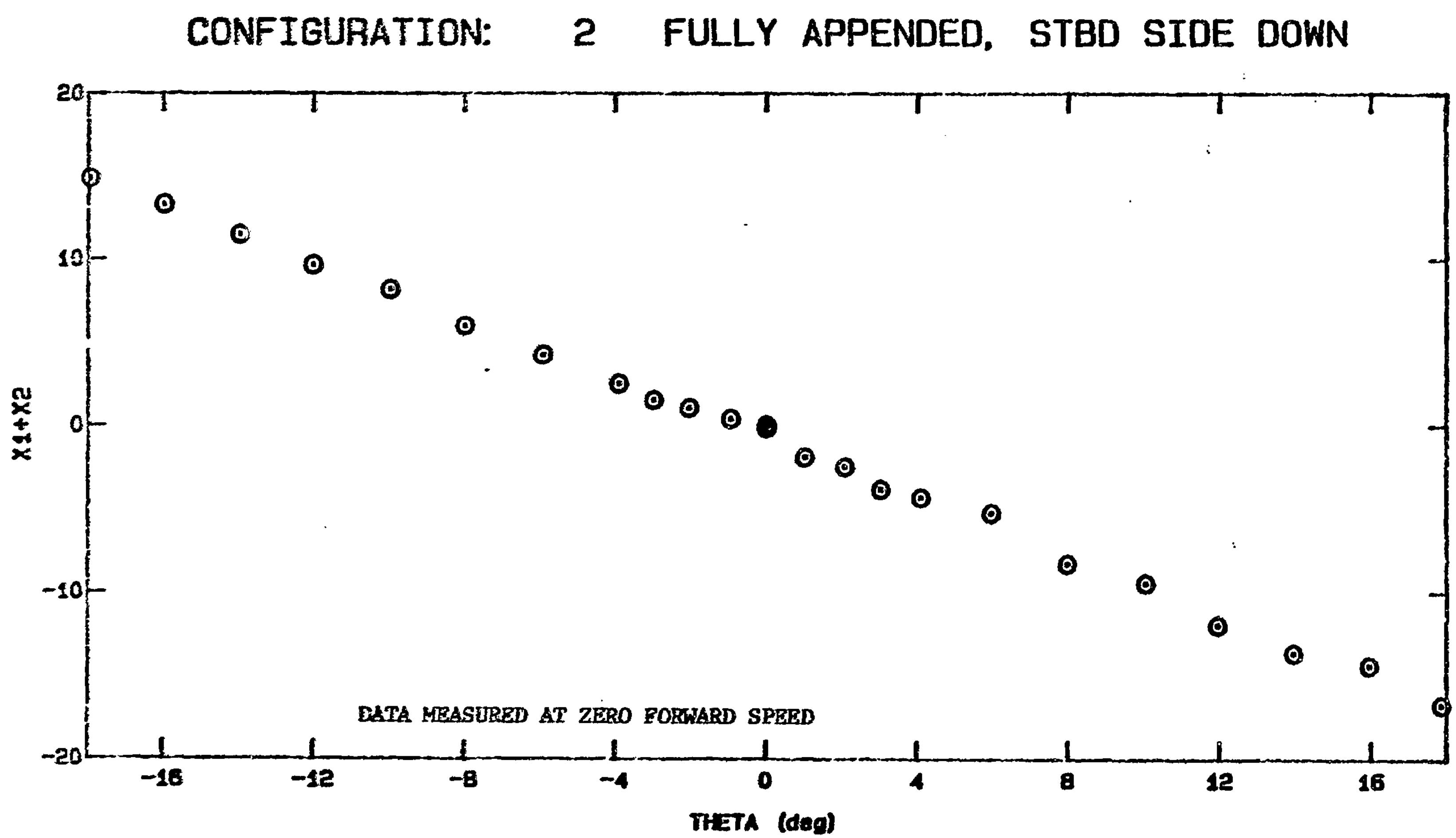

Fig. 22. Effect of tilt table angle on the longitudinal force at standstill for use in correcting the underway longitudinal force data and in determining the weight of the model in water for Configuration 2.

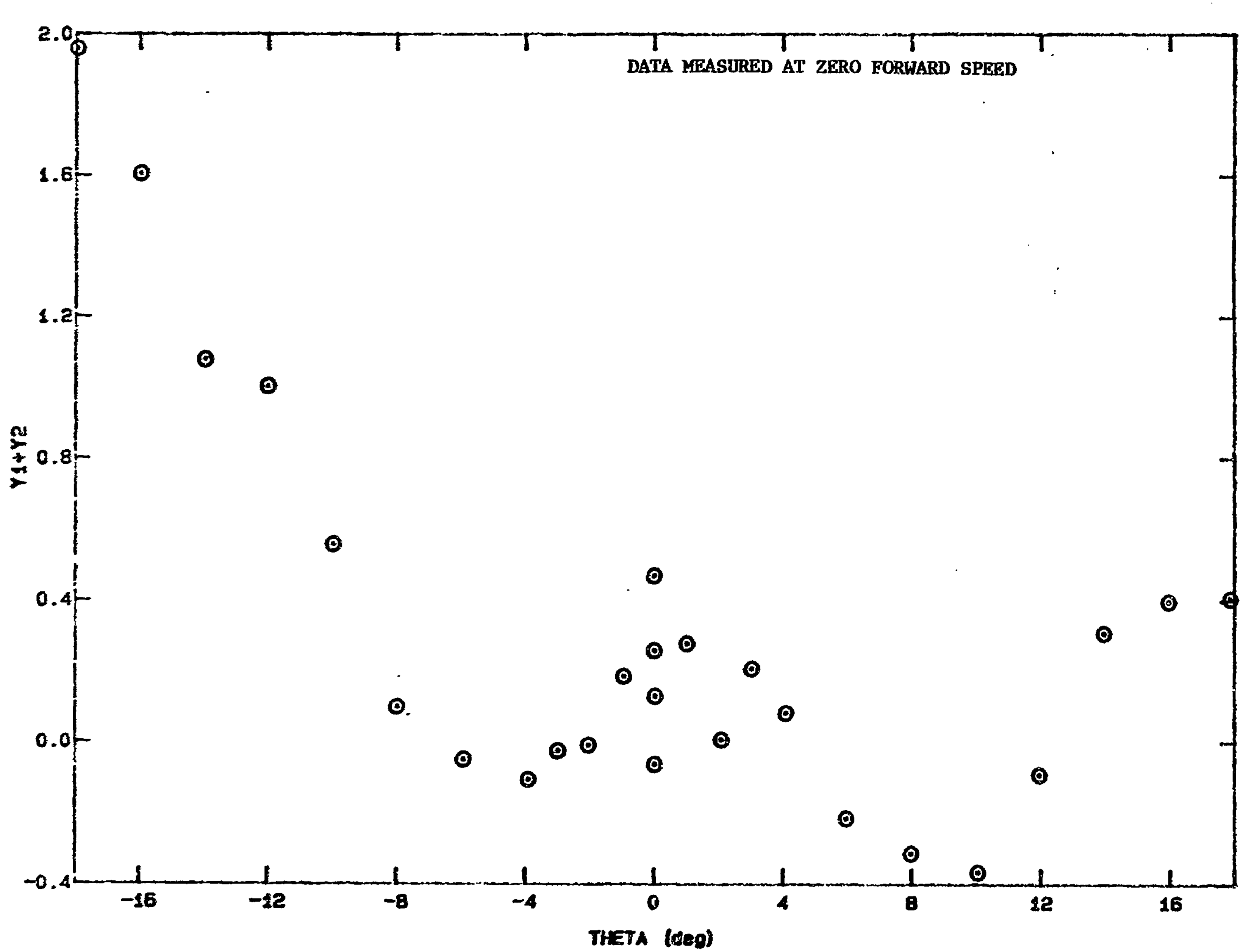

Fig. 23. Effect of tilt table angle on the lateral force at standstill for use in correcting the underway lateral force data for Configuration 2.

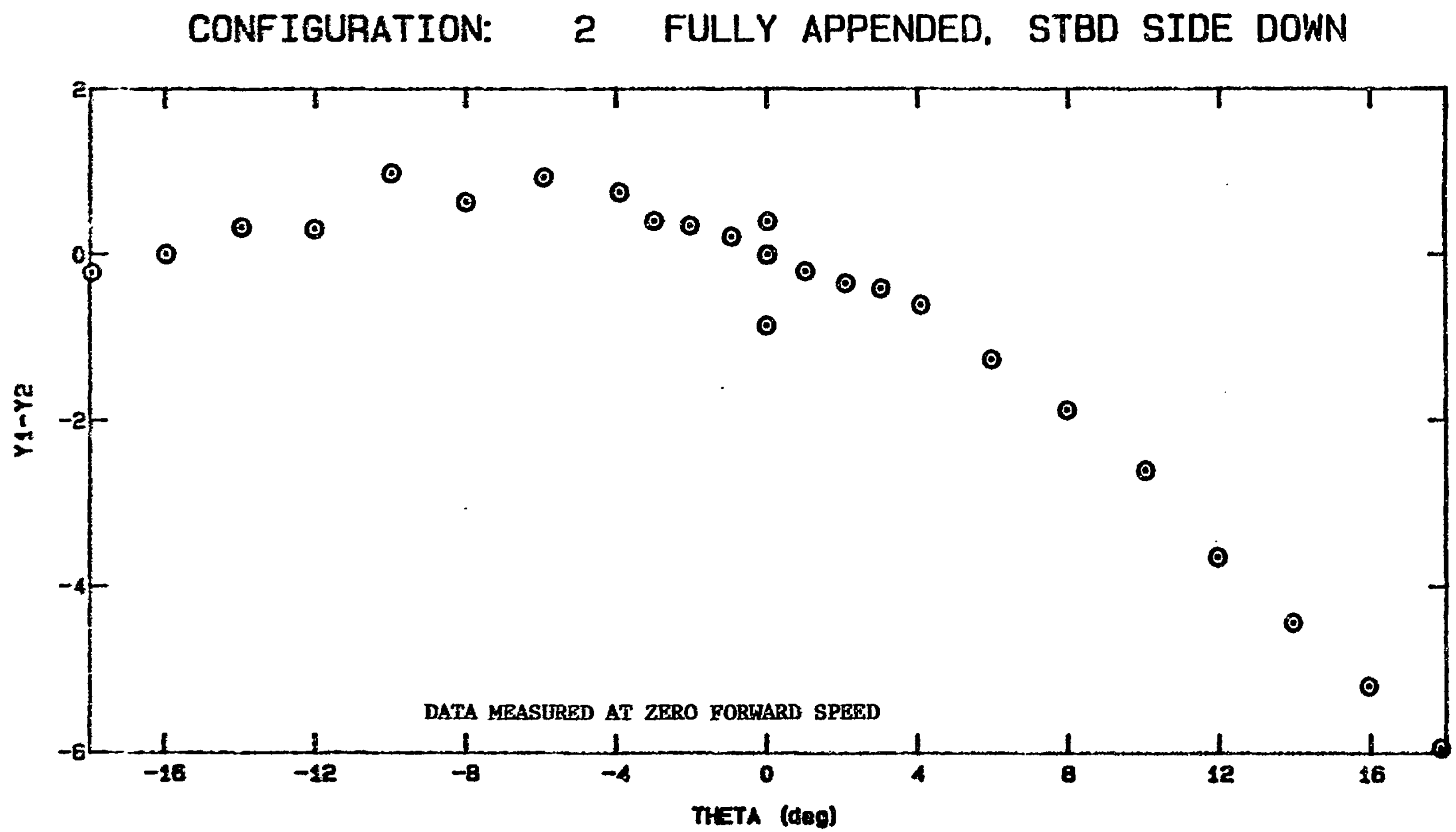

Fig. 24. Effect of tilt table angle on the difference between the forward and aft lateral force data for use in correcting the underway yawing moment data and in determining the longitudinal location of the center of gravity for Configuration 2.

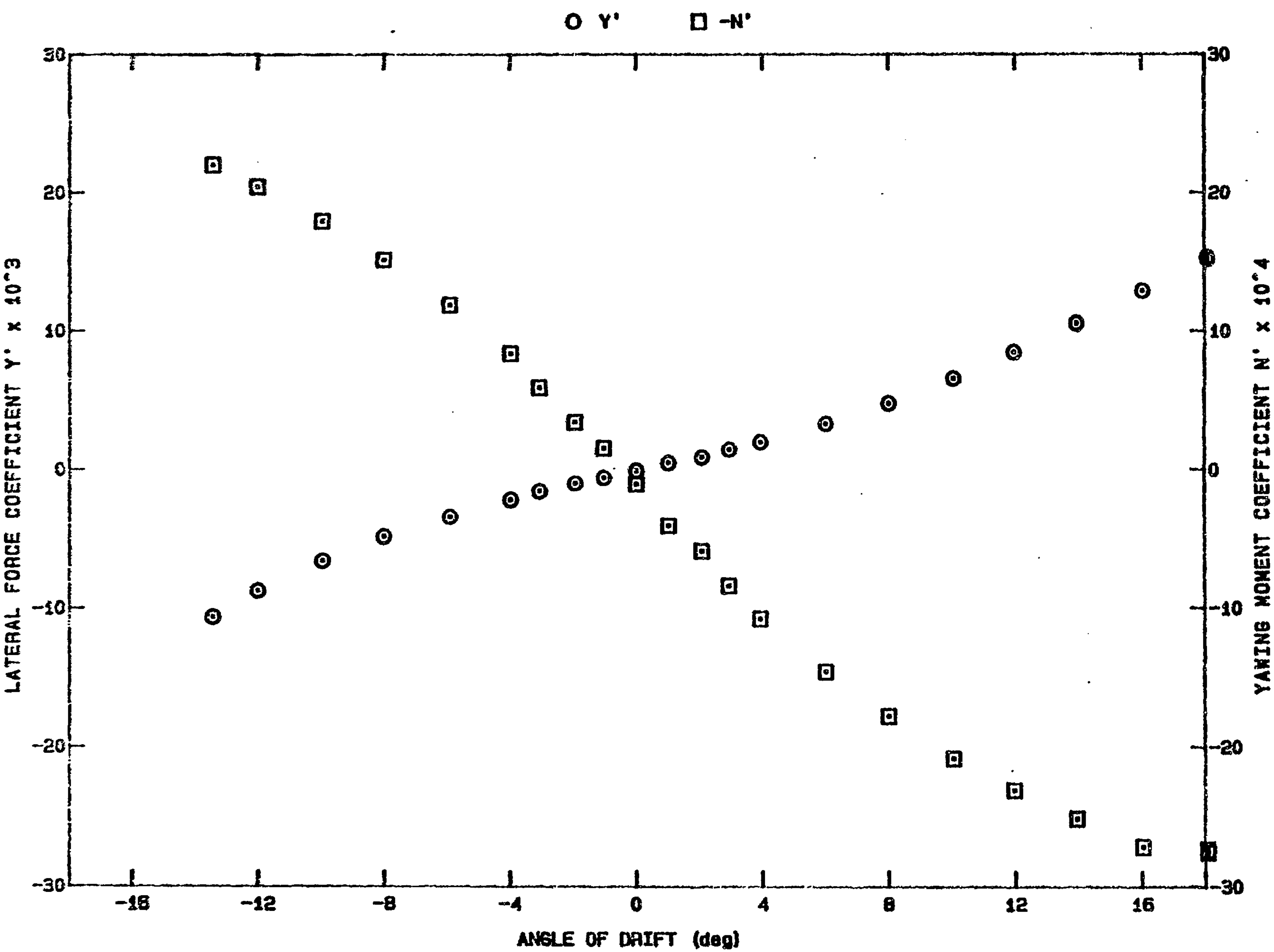

Fig. 25. Effect of angle of drift on the lateral force and yawing moment coefficients for Configuration 2.

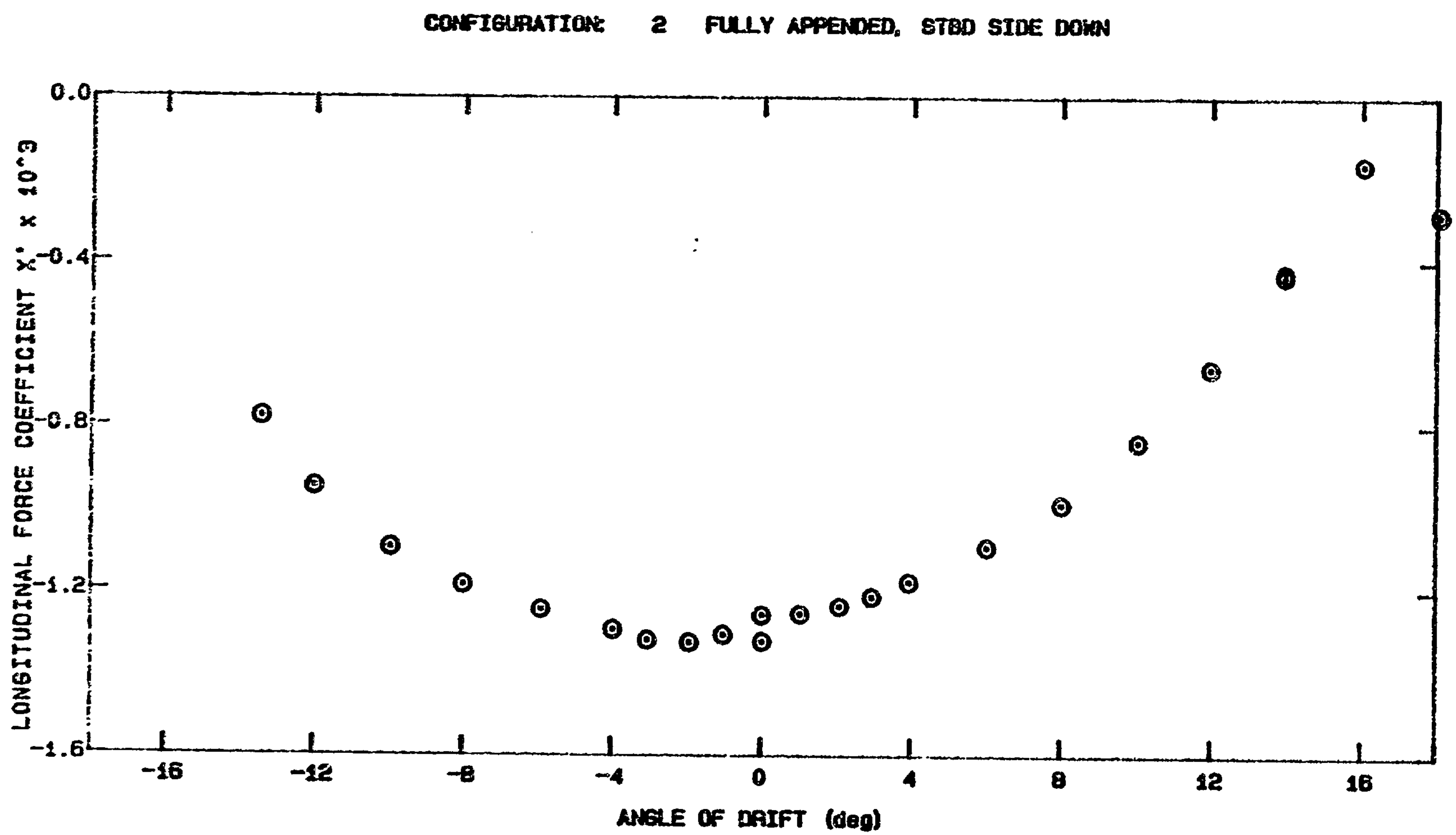

Fig. 26. Effect of angle of drift on the longitudinal force coefficient for Configurations 2.

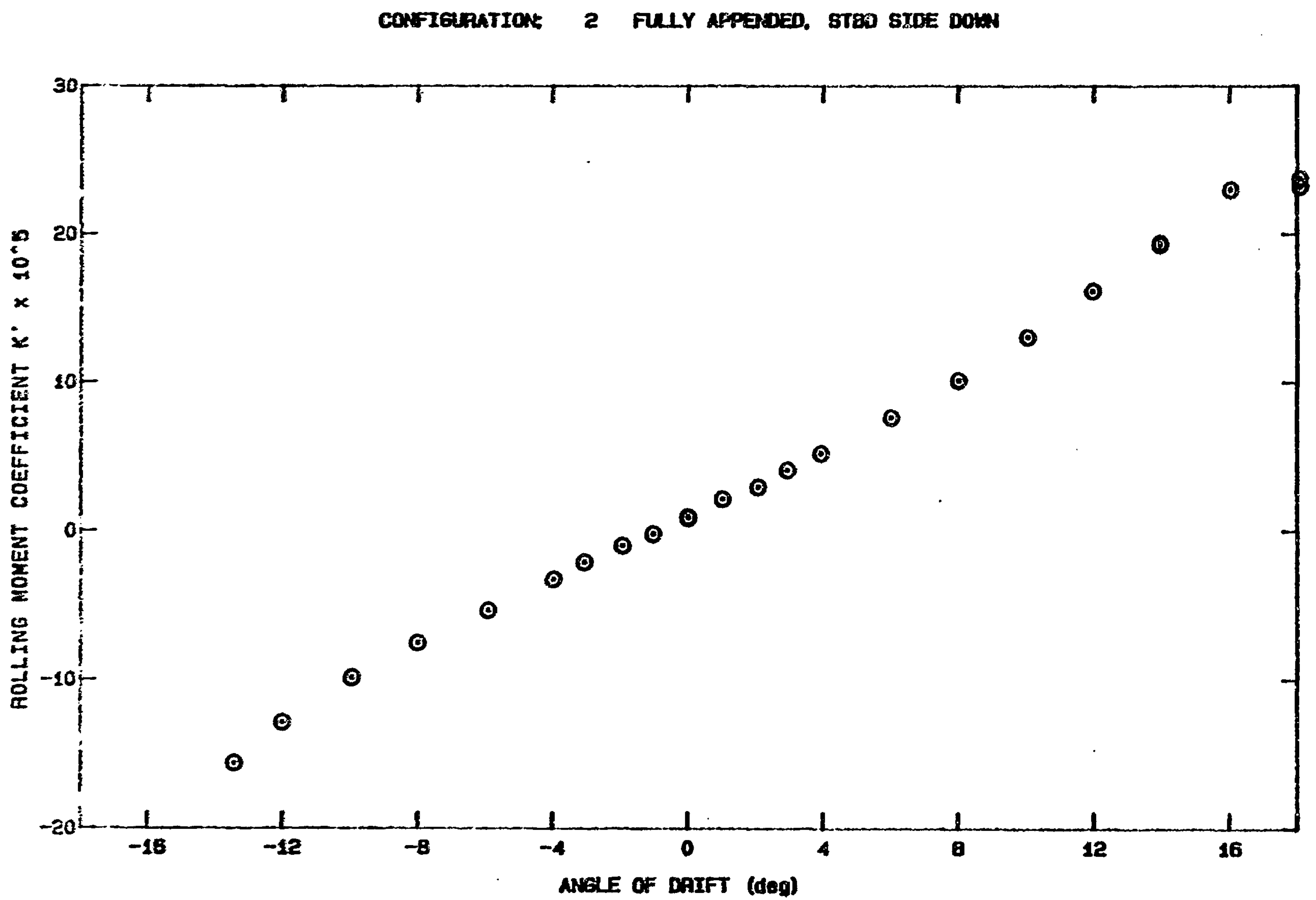

Fig. 27. Effect of angle of drift on the rolling moment coefficient for Configuration 2.

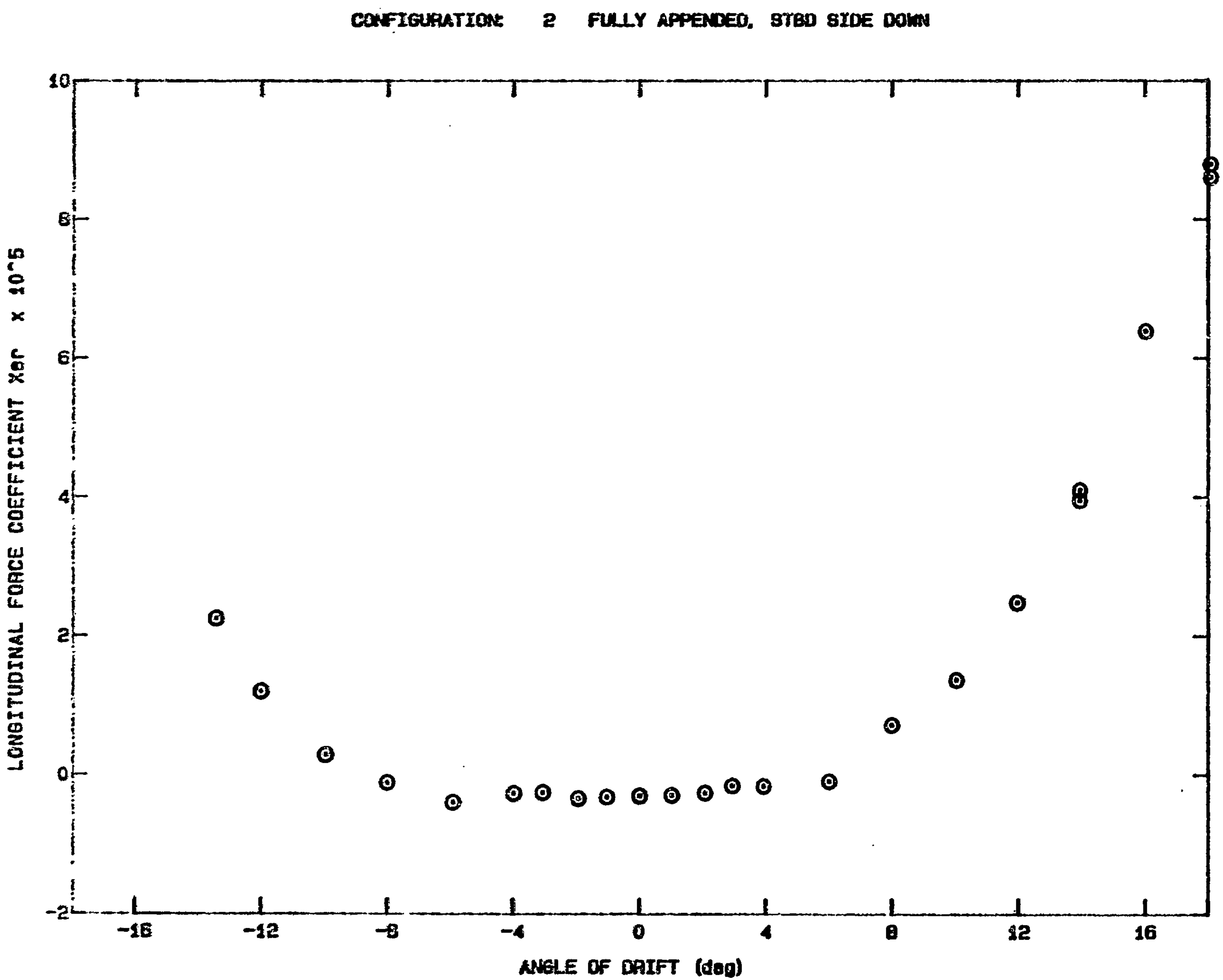

Fig. 28. Effect of angle of drift on the longitudinal force coefficient measured on one rudder for Configuration 2.

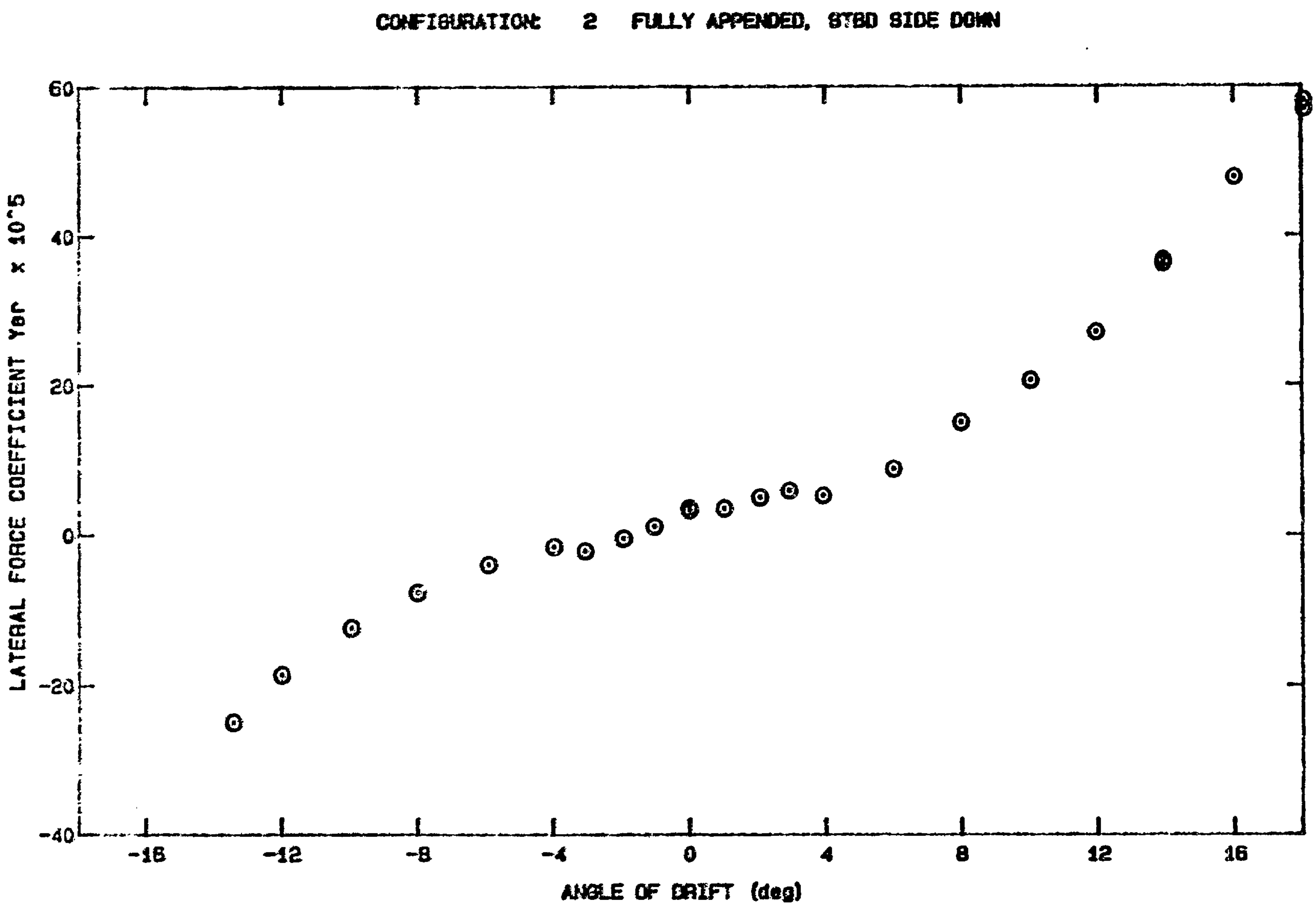

Fig. 29. Effect of angle of drift on the lateral force coefficient measured on one rudder for Configuration 2.

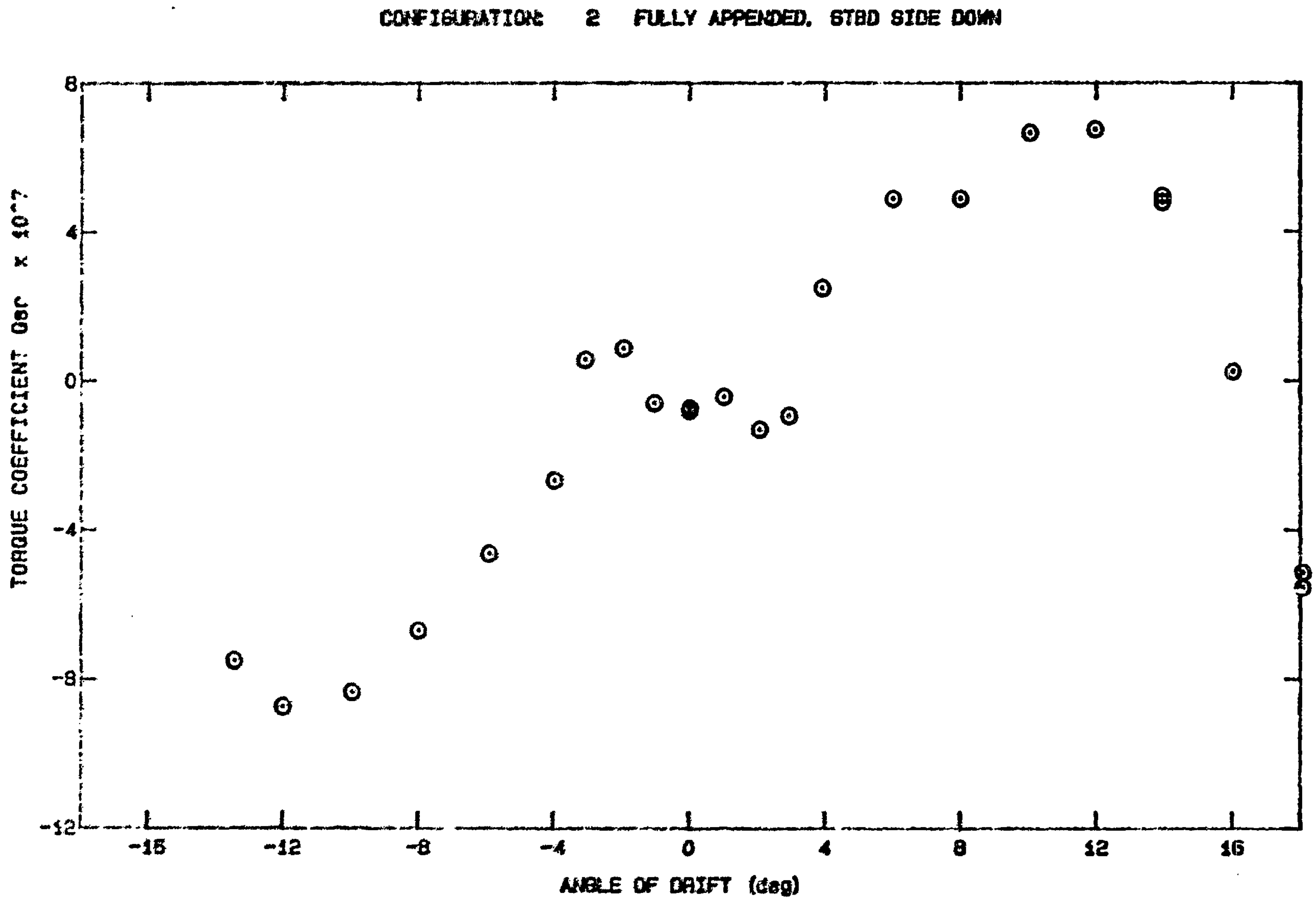

Fig. 30. Effect of angle of drift on the hydrodynamic torque coefficient measured on the stock of one rudder for Configuration 2.

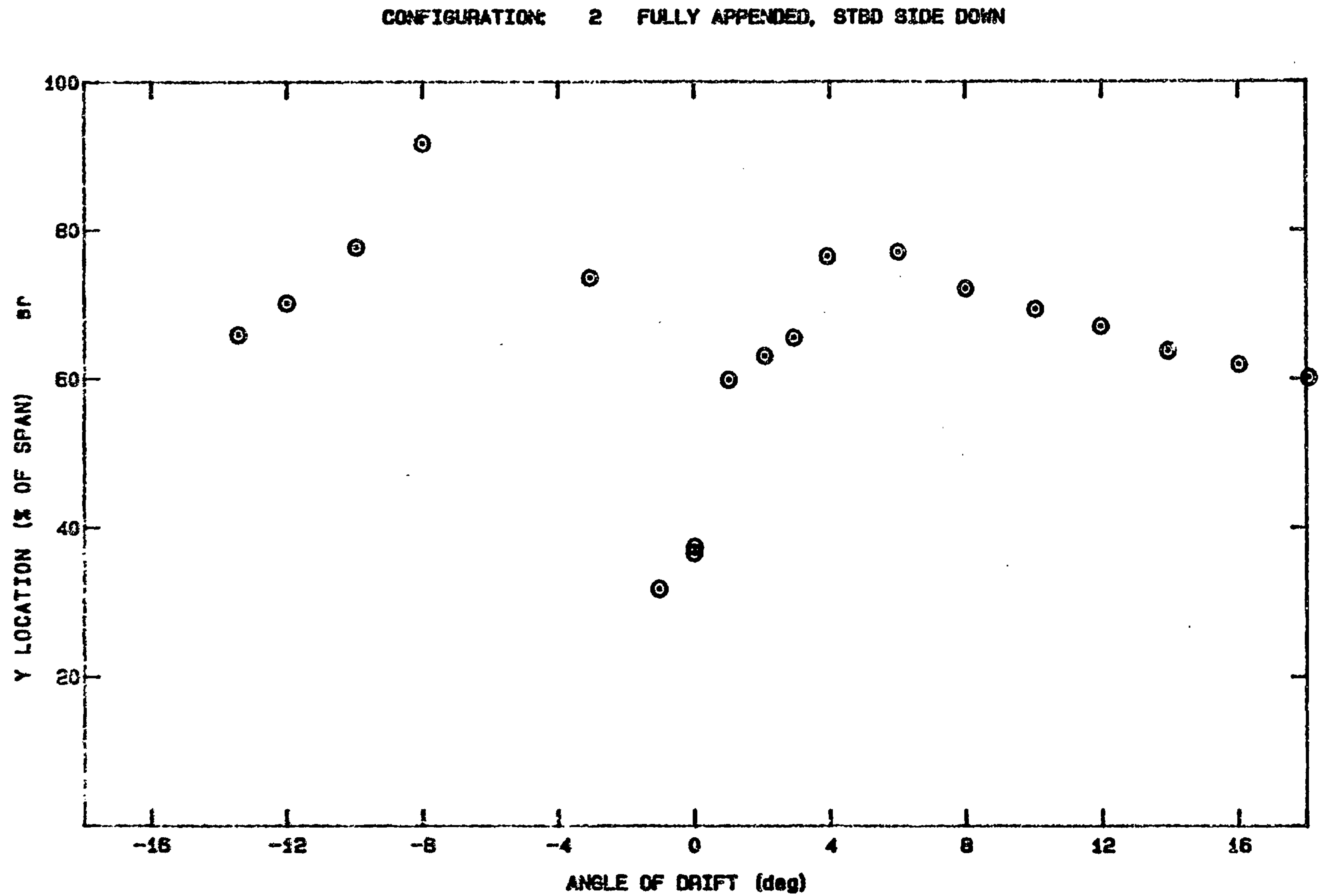

Fig. 31. Effect of angle of drift on the percent spanwise location of the center of pressure measured on one rudder for Configuration 2.

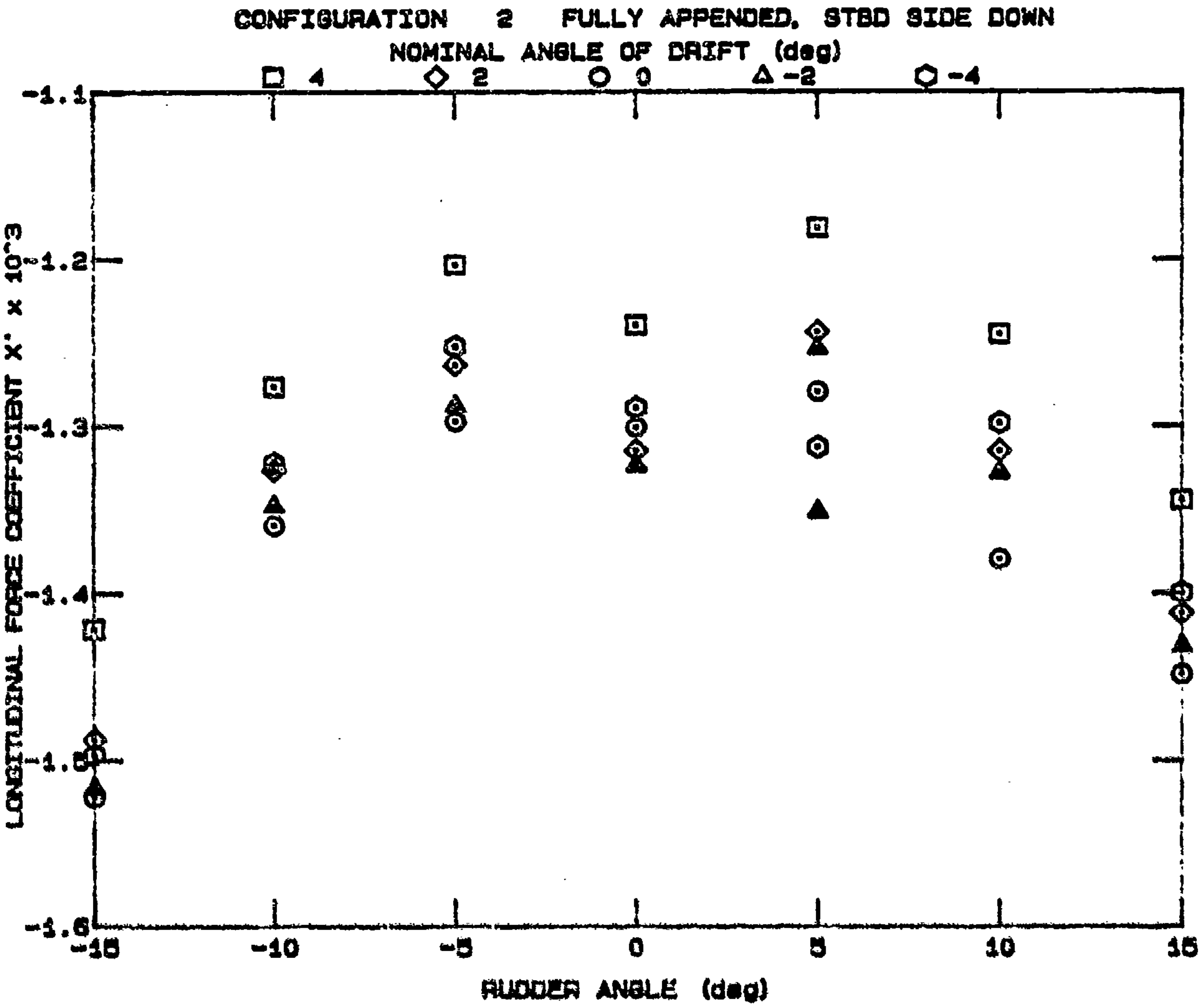

Fig. 32. Effect of rudder angle on the longitudinal force coefficient for various angles of drift for Configuration 2.

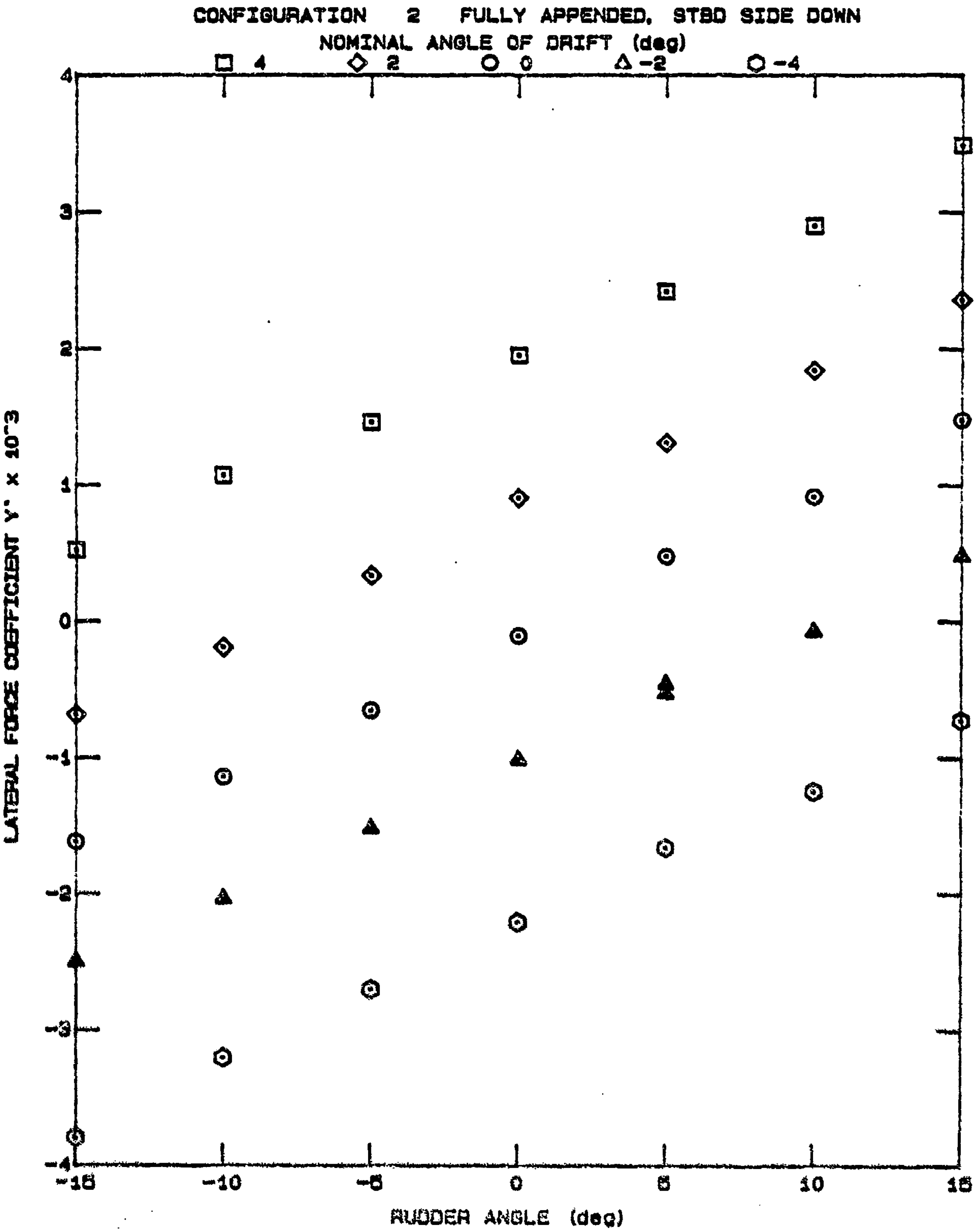

Fig. 33. Effect of rudder angle on the lateral force coefficient for various angles of drift for Configuration 2.

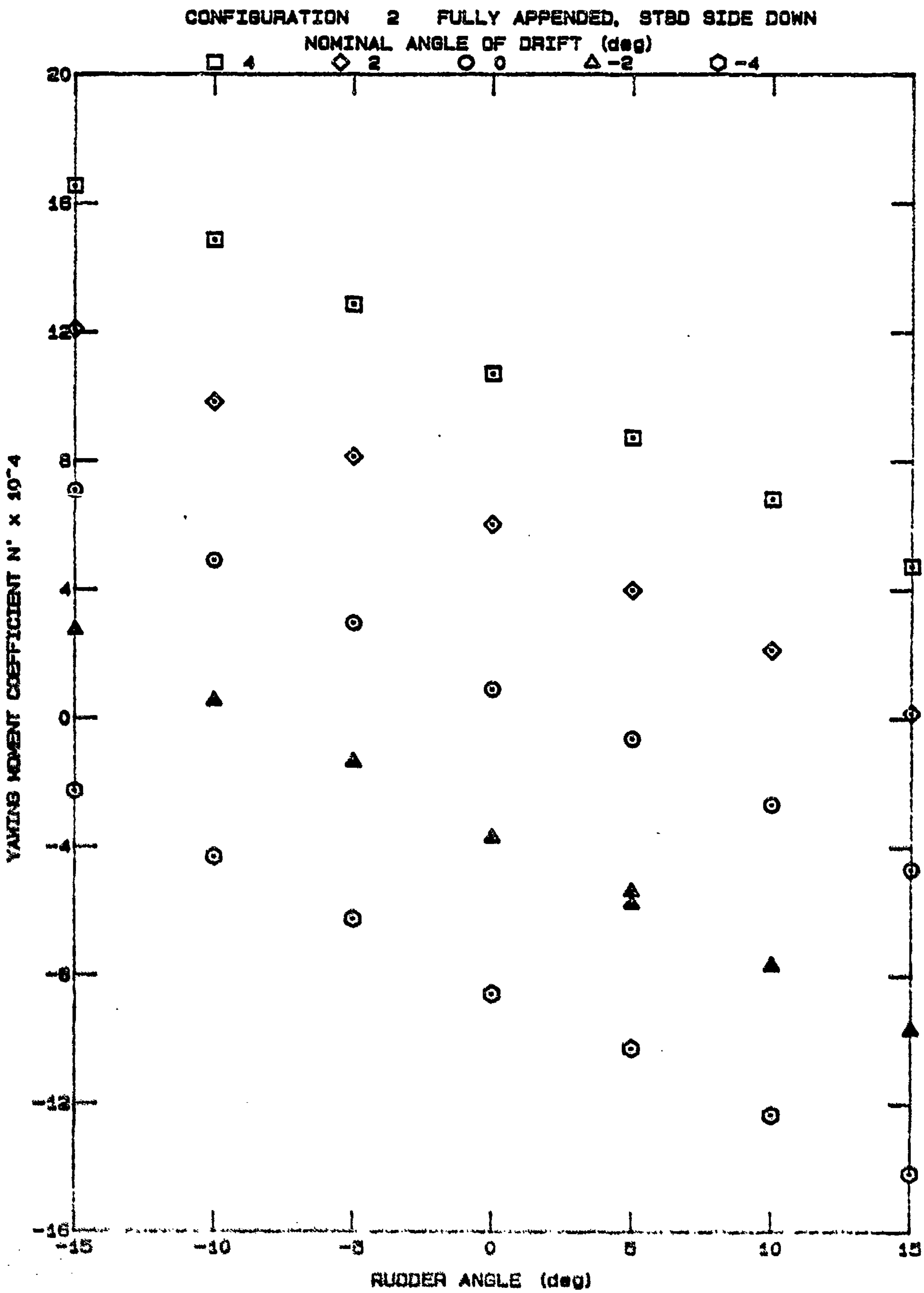

Fig. 34. Effect of rudder angle on the yawing moment coefficient for various angles of drift for Configuration 2.

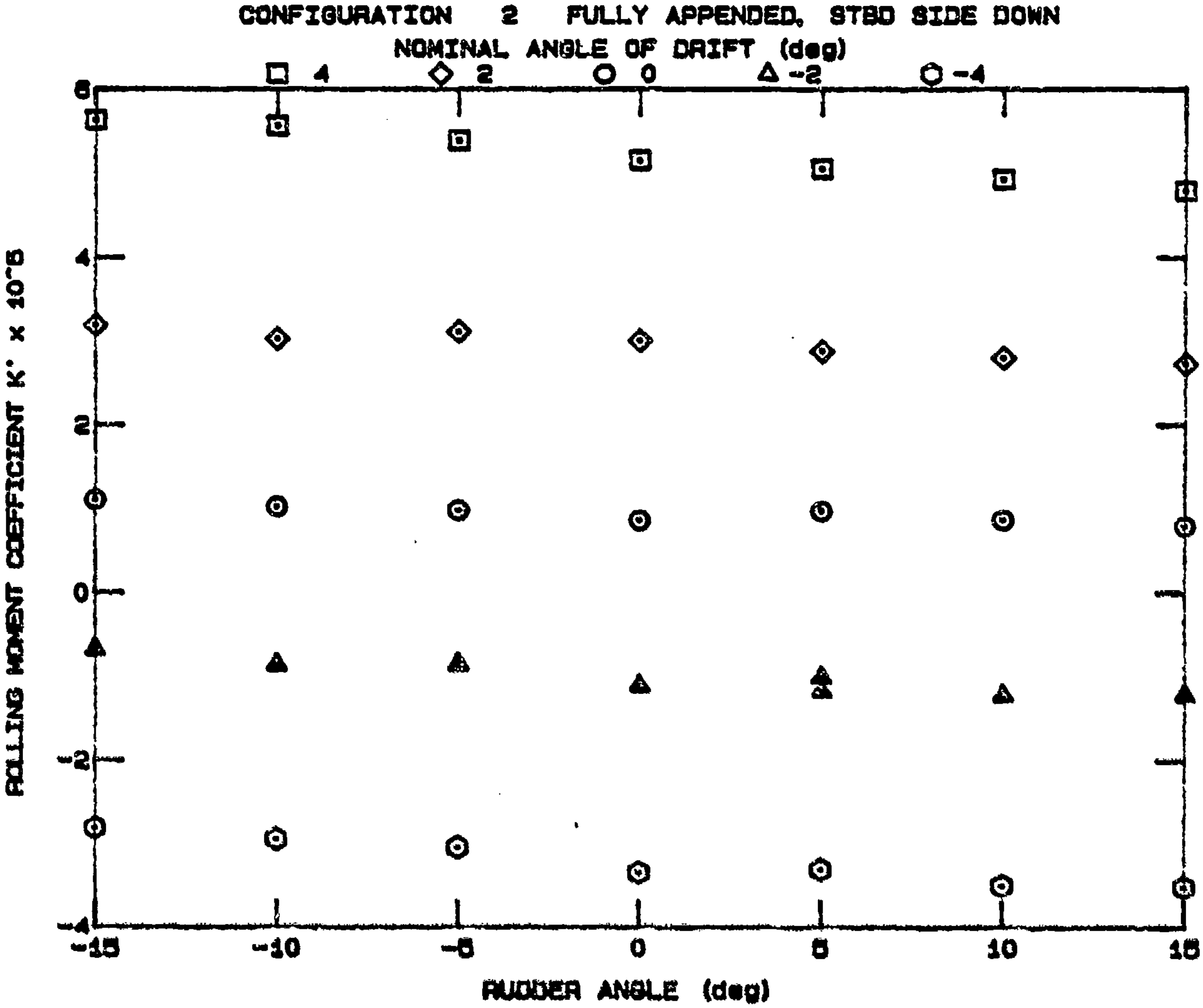

Fig. 35. Effect of rudder angle on the rolling moment coefficient for various angles of drift for Configuration 2.

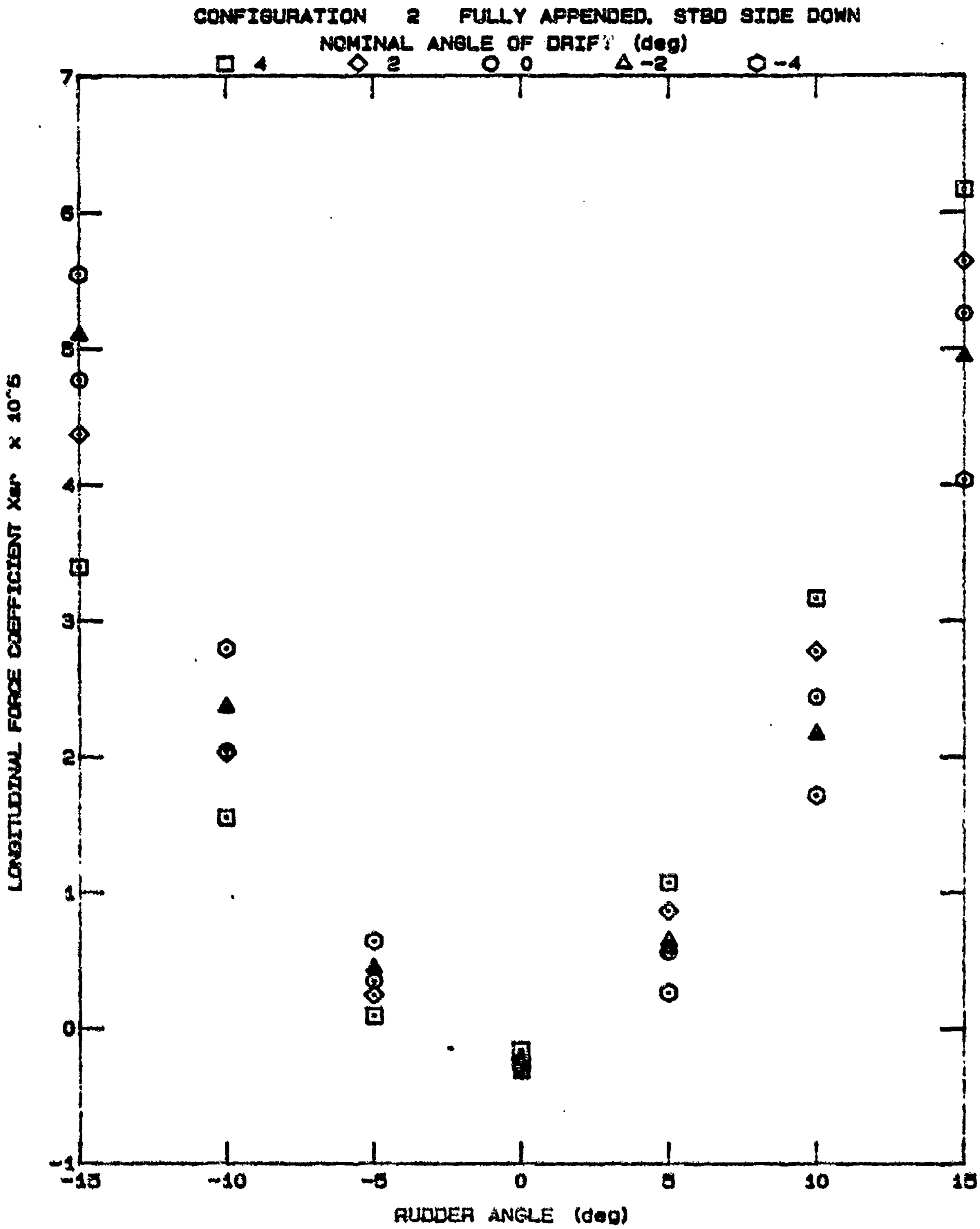

Fig. 36. Effect of rudder angle on the longitudinal force coefficient for various angles of drift measured on one rudder for Configuration 2.

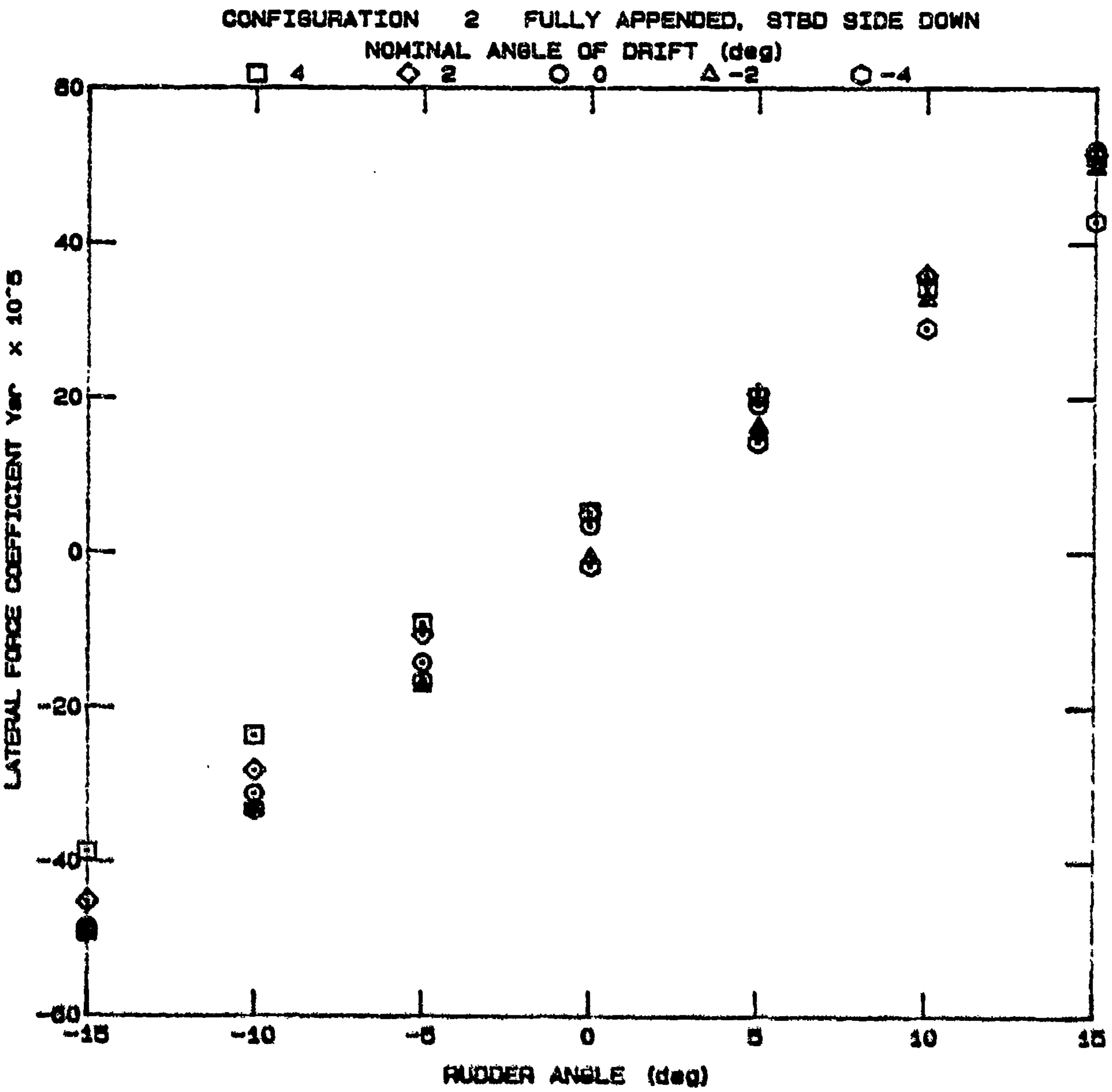

Fig. 37. Effect of rudder angle on the lateral force coefficient for various angles of drift measured on one rudder for Configuration 2.

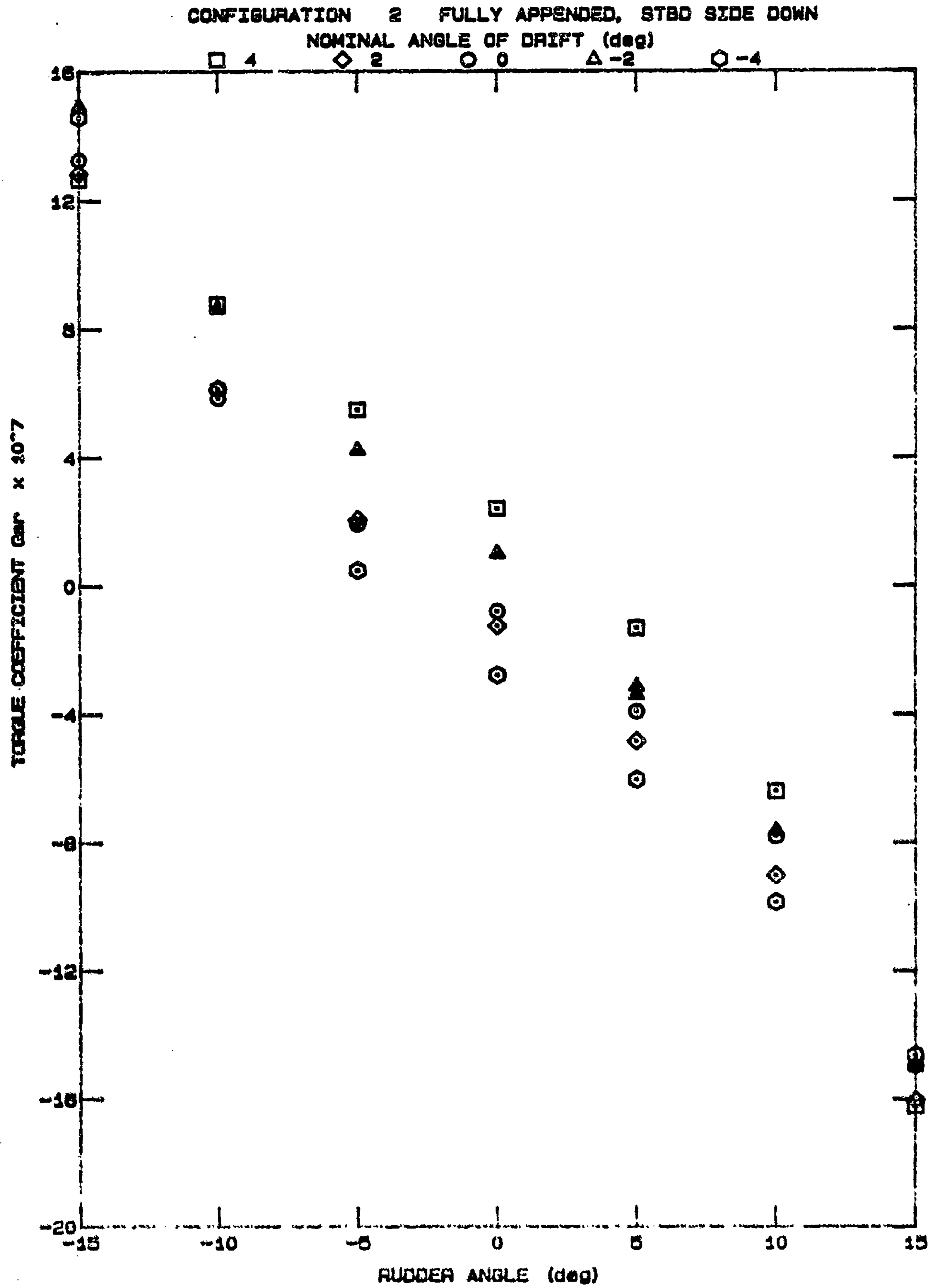

Fig. 38. Effect of rudder angle on the hydrodynamic torque coefficient for various angles of drift measured on the stock of one rudder for Configuration 2.

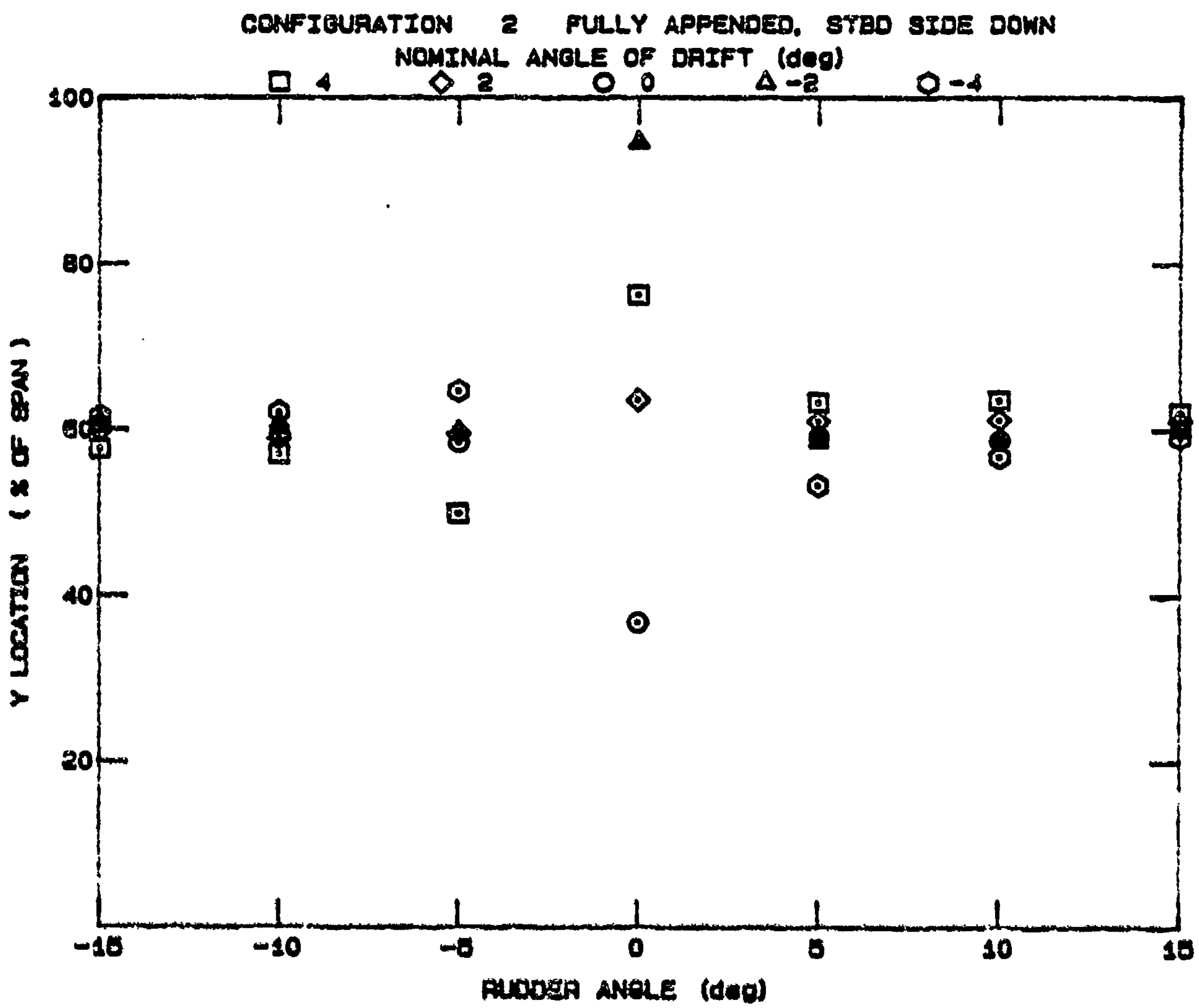

Fig. 39. Effect of rudder angle on the percent spanwise location of the center of pressure measured on one rudder for Configuration 2.

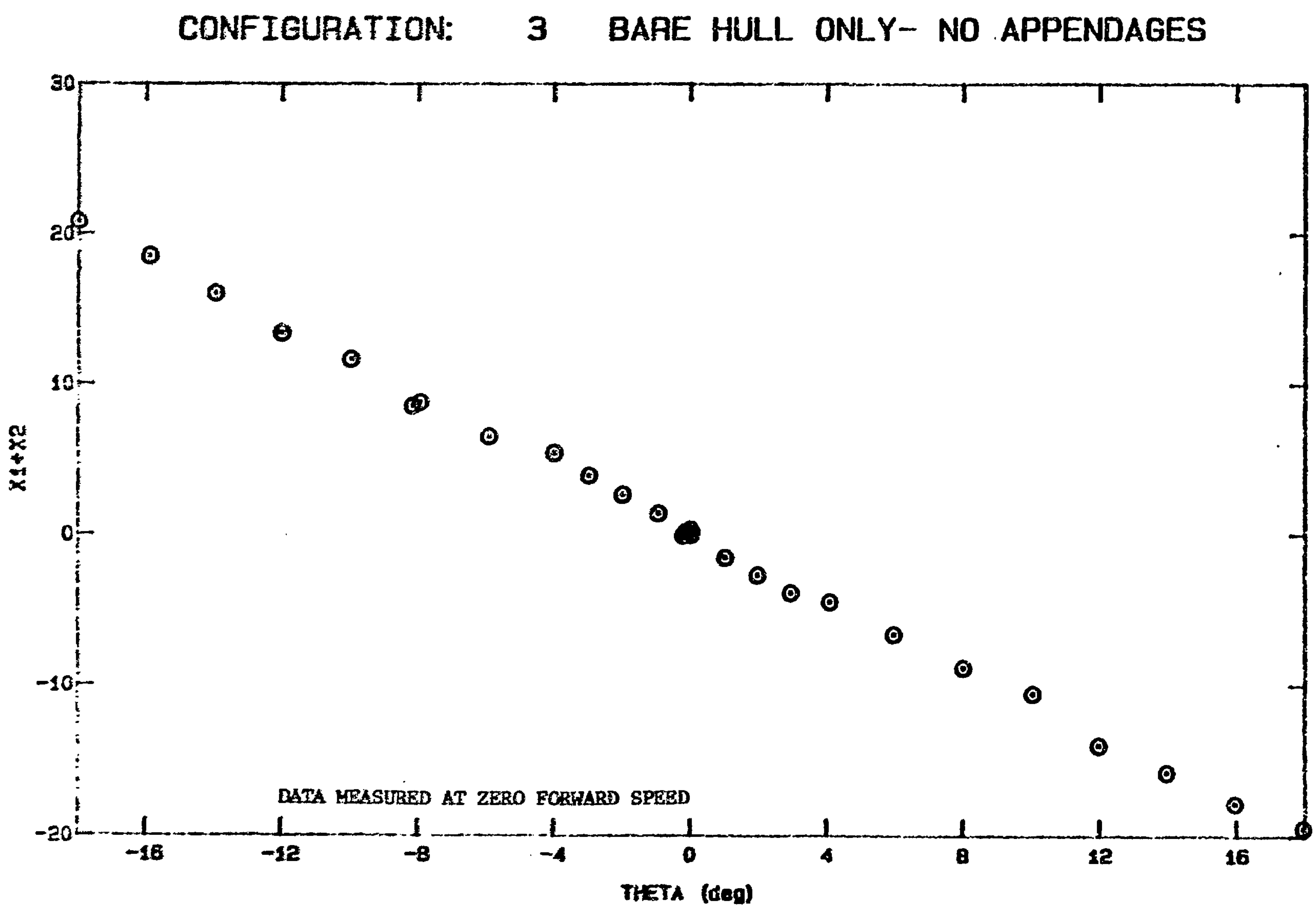

Fig. 40. Effect of tilt table angle on the longitudinal force at standstill for use in correcting the underway longitudinal force data and in determining the weight of the model in water for Configuration 3.

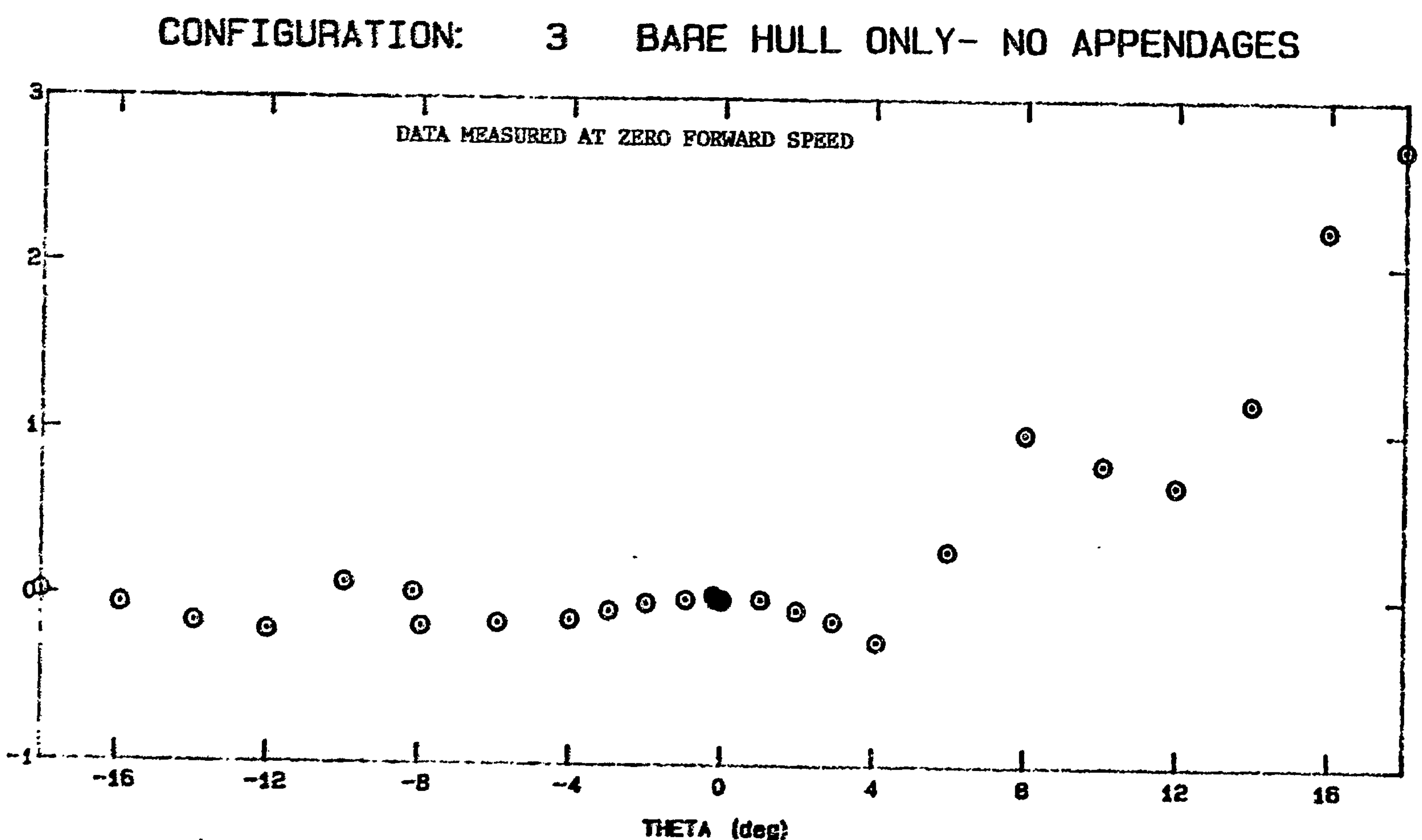

Fig. 41. Effect of tilt table angle on the lateral force at standstill for use in correcting the underway lateral force data for Configuration 3.

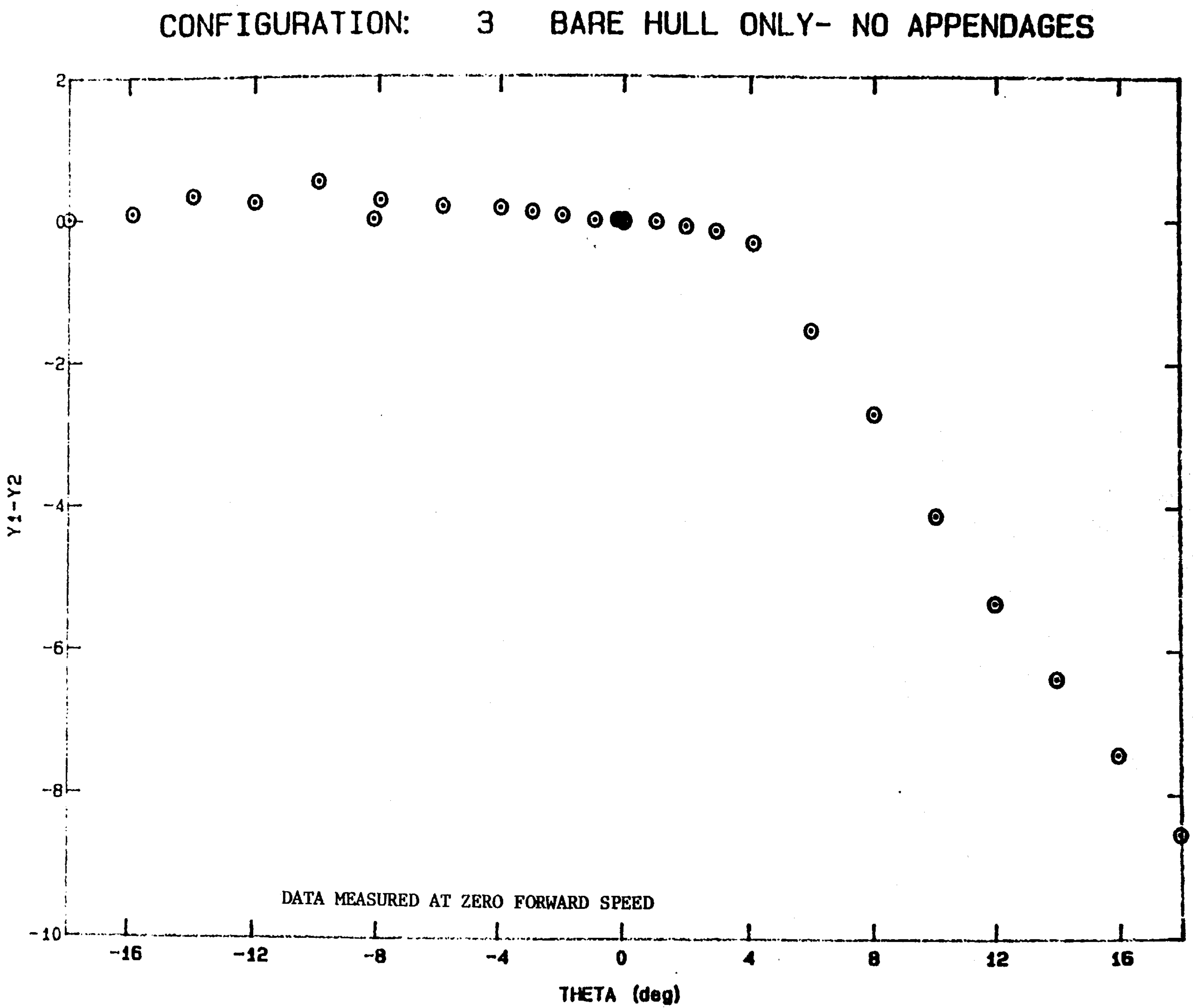

Fig. 42. Effect of tilt table angle on the difference between the forward and aft lateral force data for use in correcting the underway yawing moment data and in determining the longitudinal location

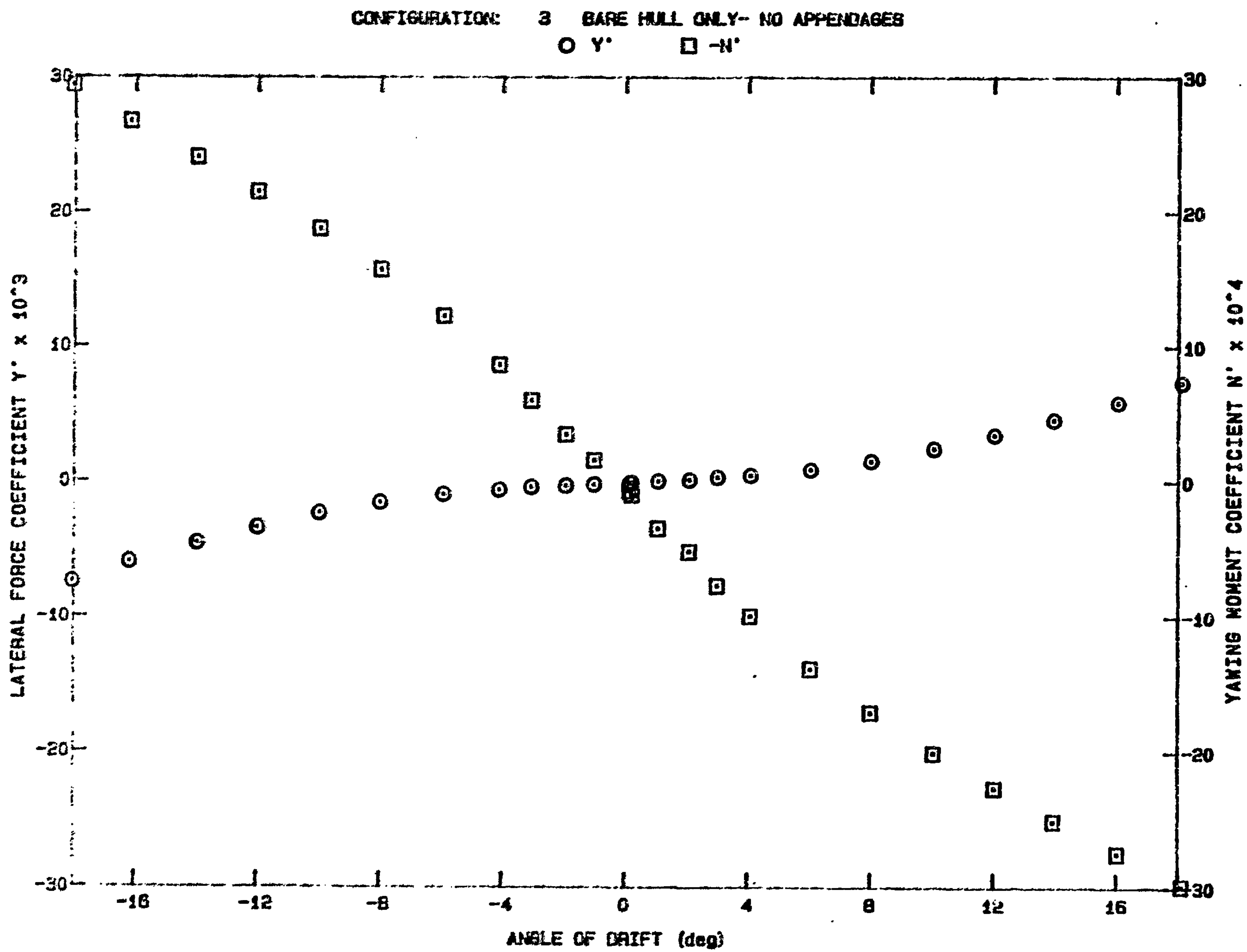

Fig. 43. Effect of angle of drift on the lateral force and yawing moment coefficients for Configuration 3.

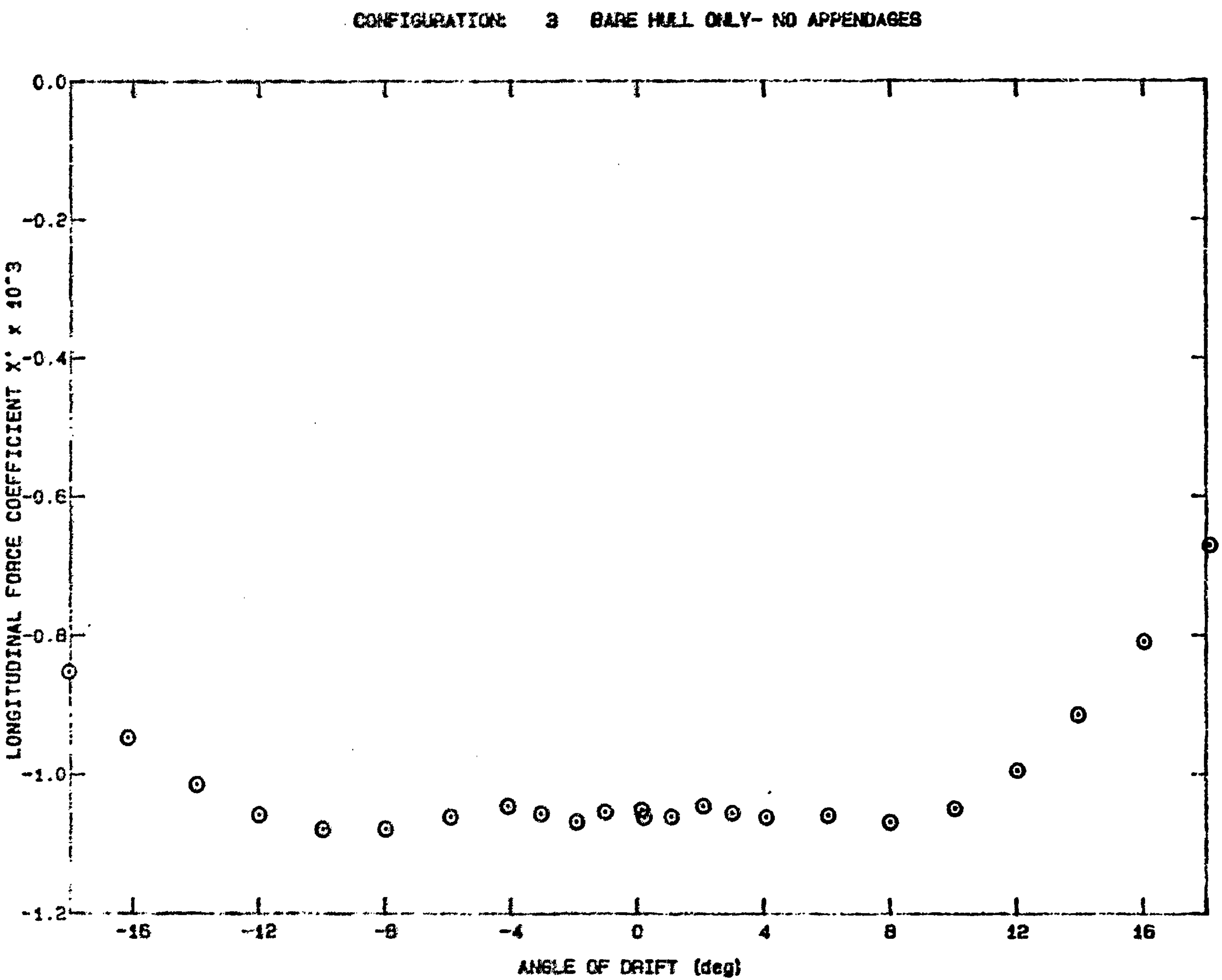

Fig. 44. Effect of angle of drift on the longitudinal force coefficient for Configurations 3.

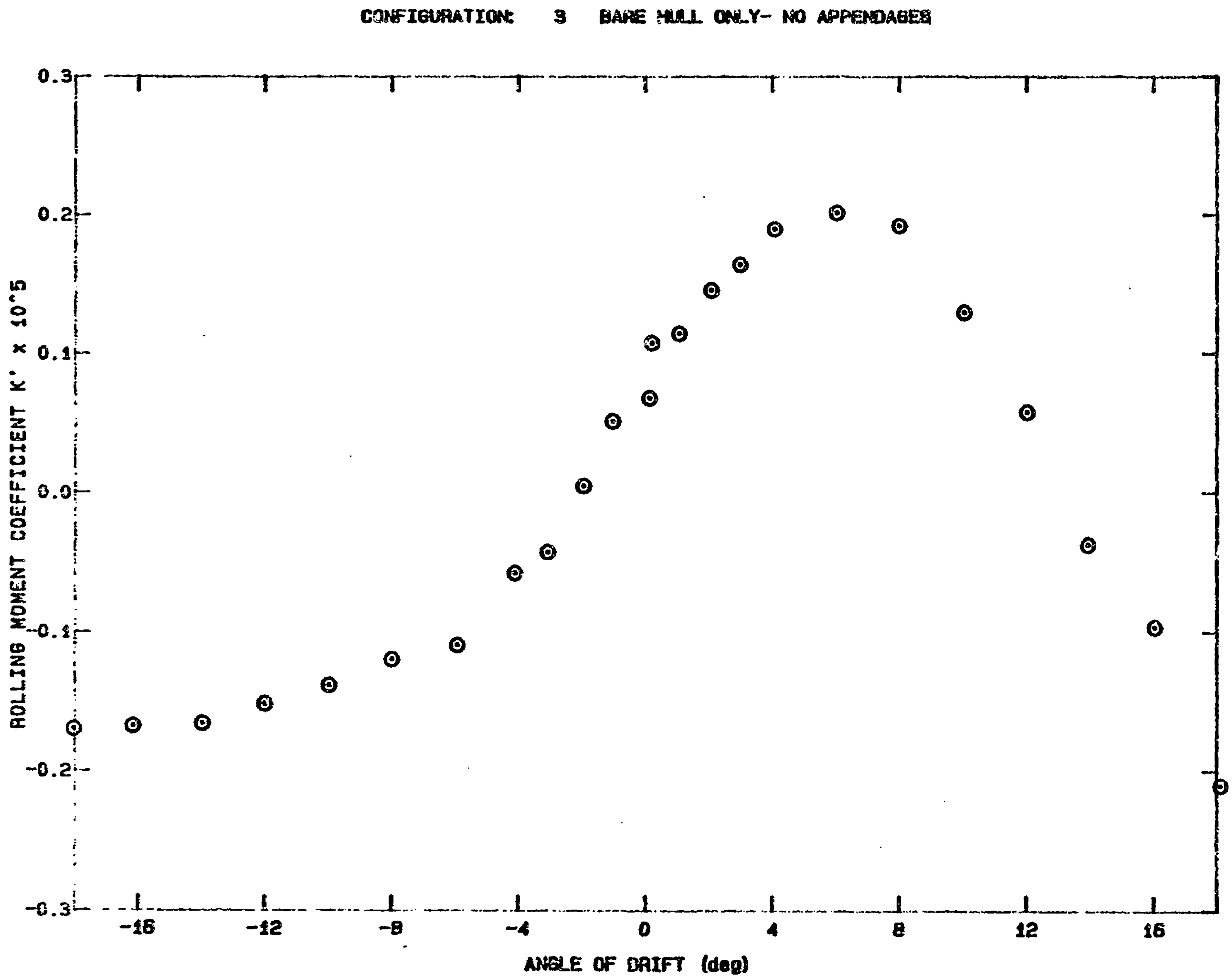

Fig. 45. Effect of angle of drift on the rolling moment coefficient for Configuration 3.

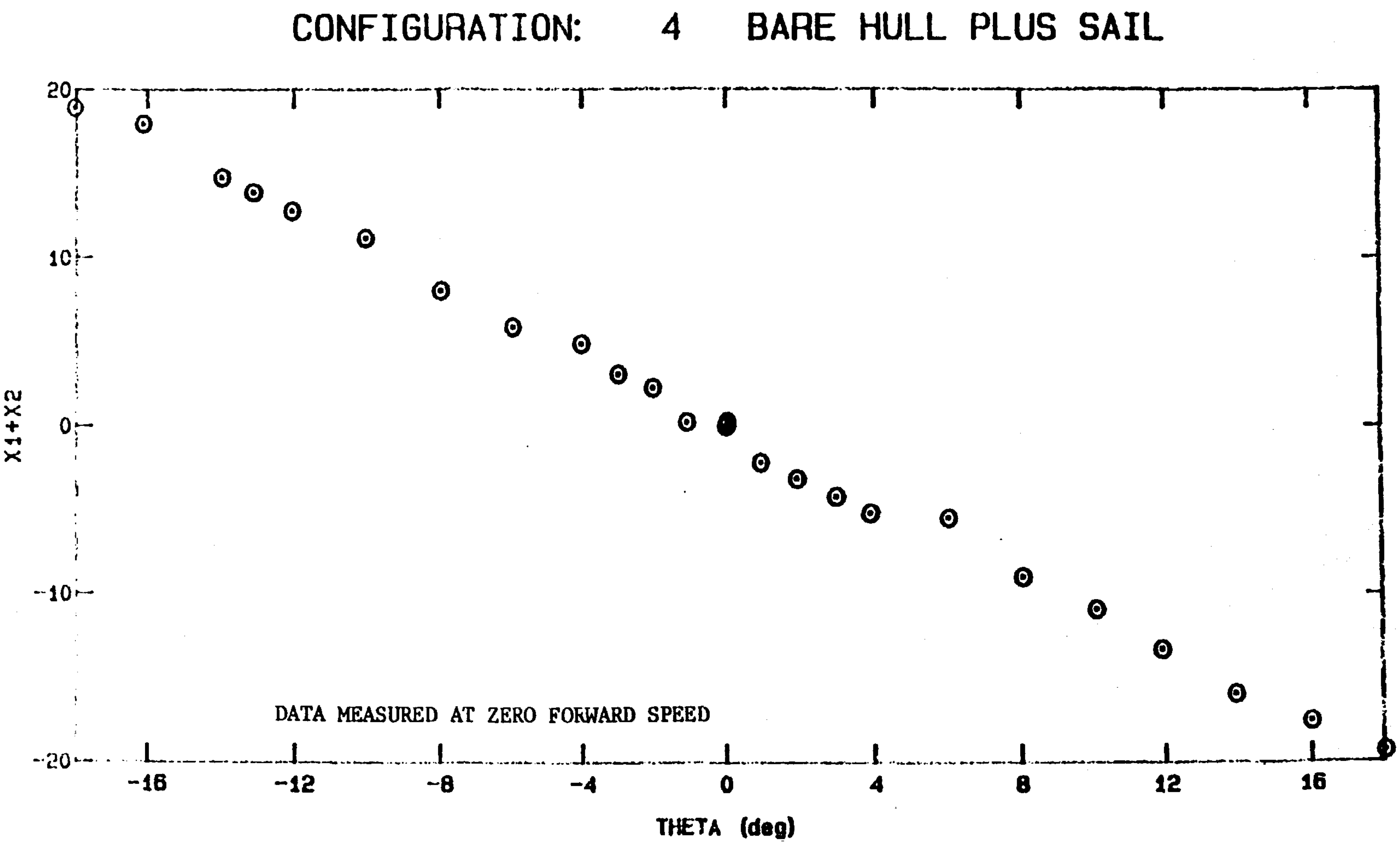

Fig. 46. Effect of tilt table angle on the longitudinal force at standstill for use in correcting the underway longitudinal force data and in determining the weight of the model in water for Configuration 4.

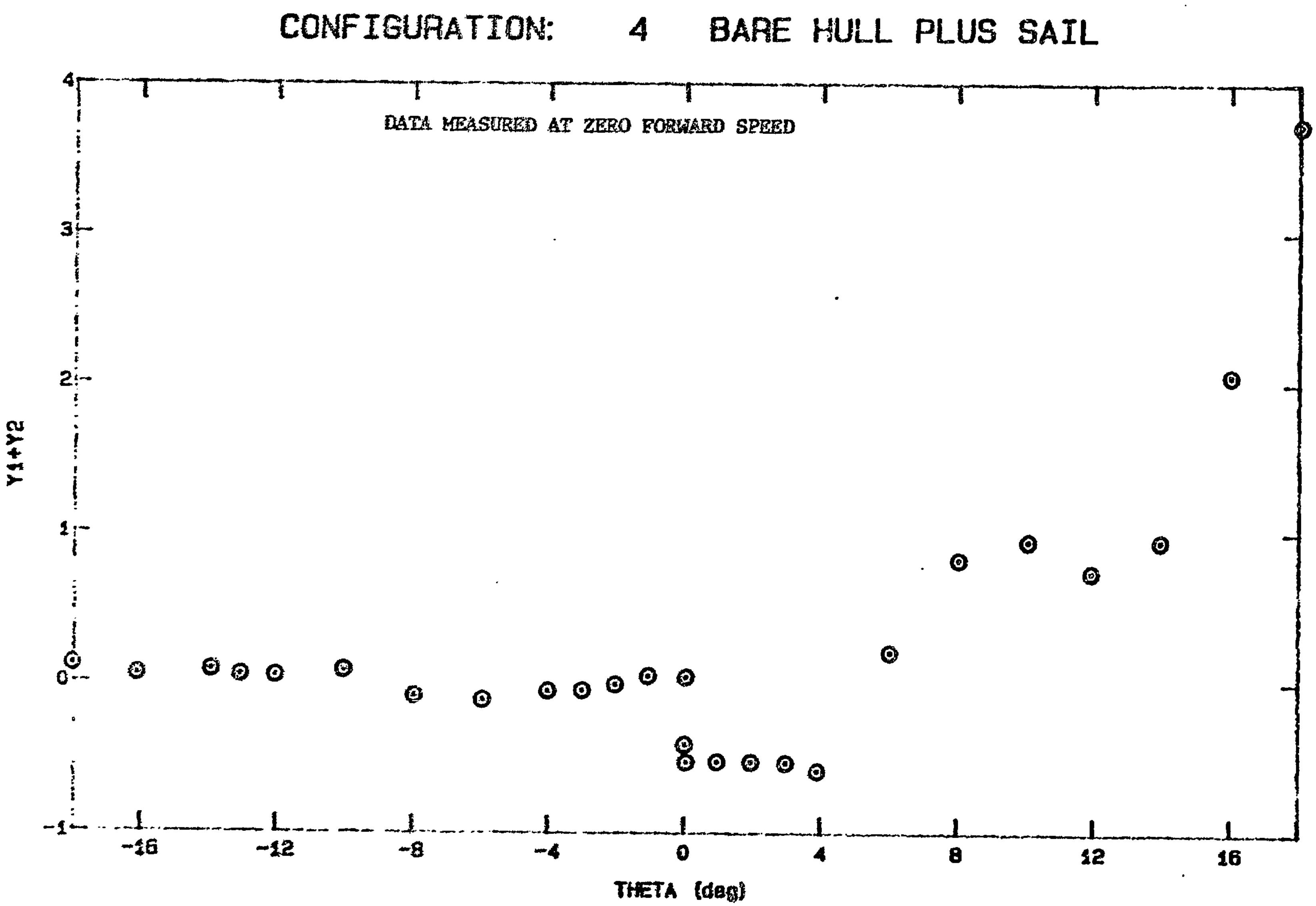

Fig. 47. Effect of tilt table angle on the lateral force at standstill for use in correcting the underway lateral force data for Configuration 4.

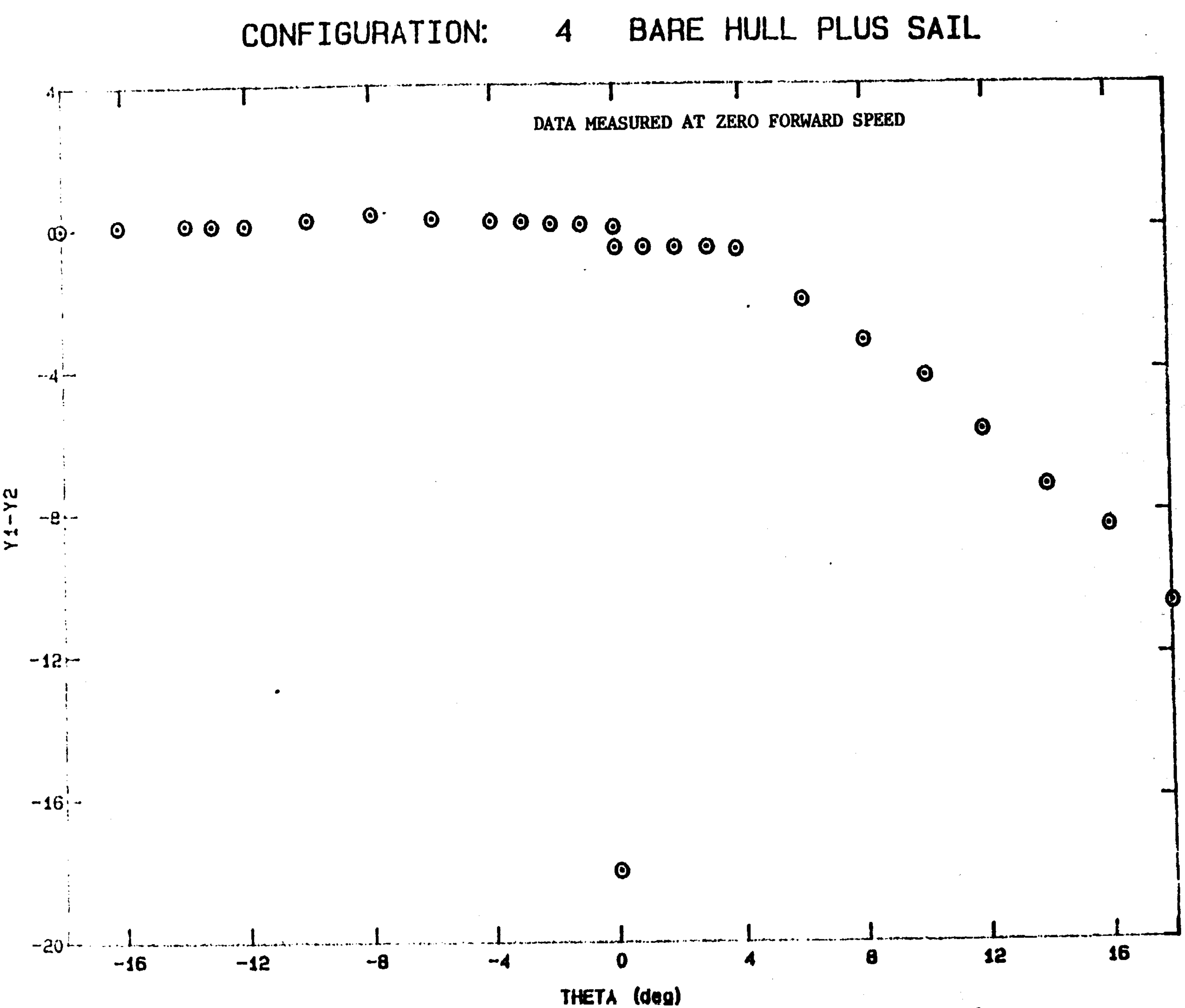

Fig. 48. Effect of tilt table angle on the difference between the forward and aft lateral force data for use in correcting the underway yawing moment data and in determining the longitudinal location of the center of gravity for Configuration 4.

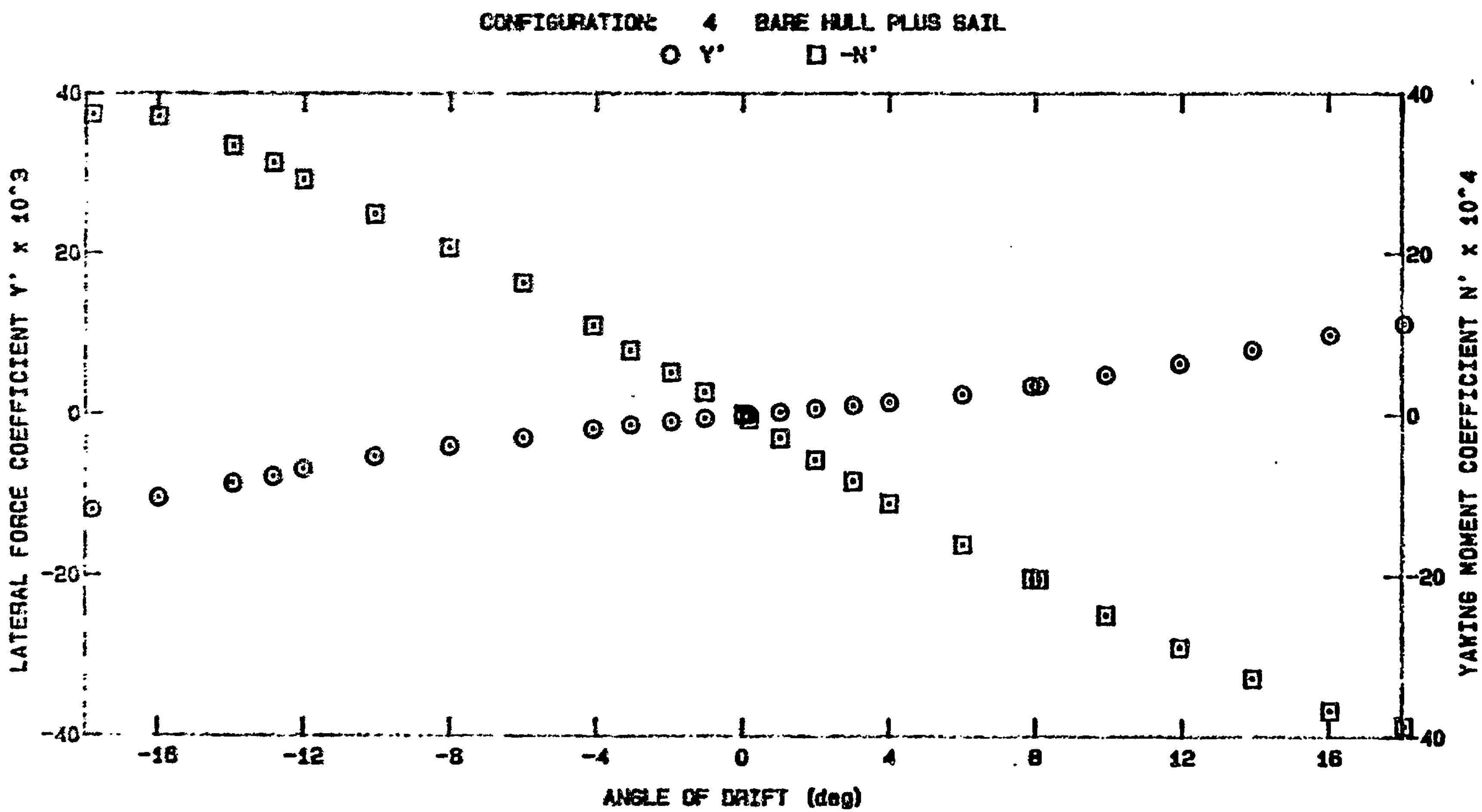

Fig. 49. Effect of angle of drift on the lateral force and yawing moment coefficients for Configuration 4.

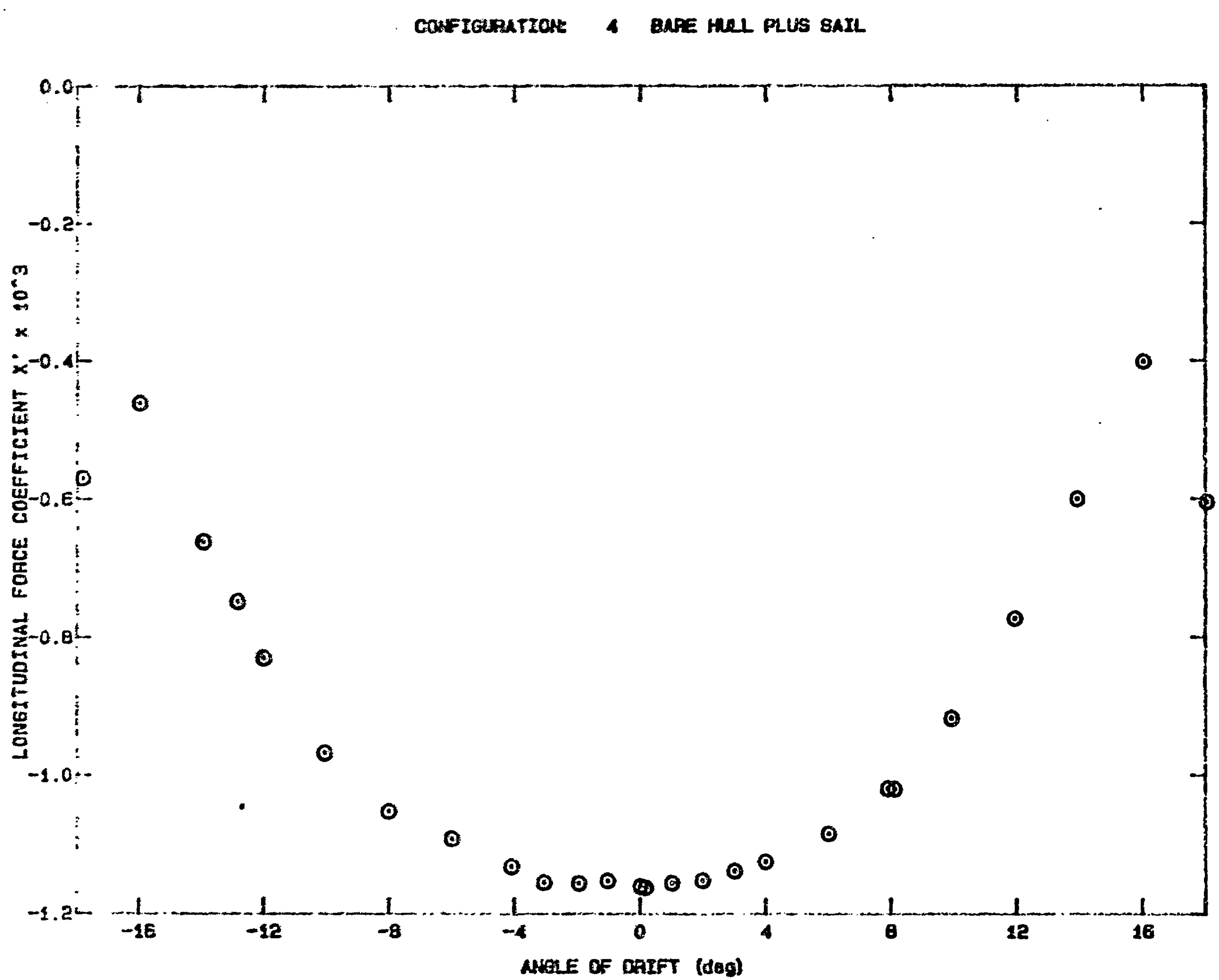

Fig. 50. Effect of angle of drift on the longitudinal force coefficient for Configurations 4.

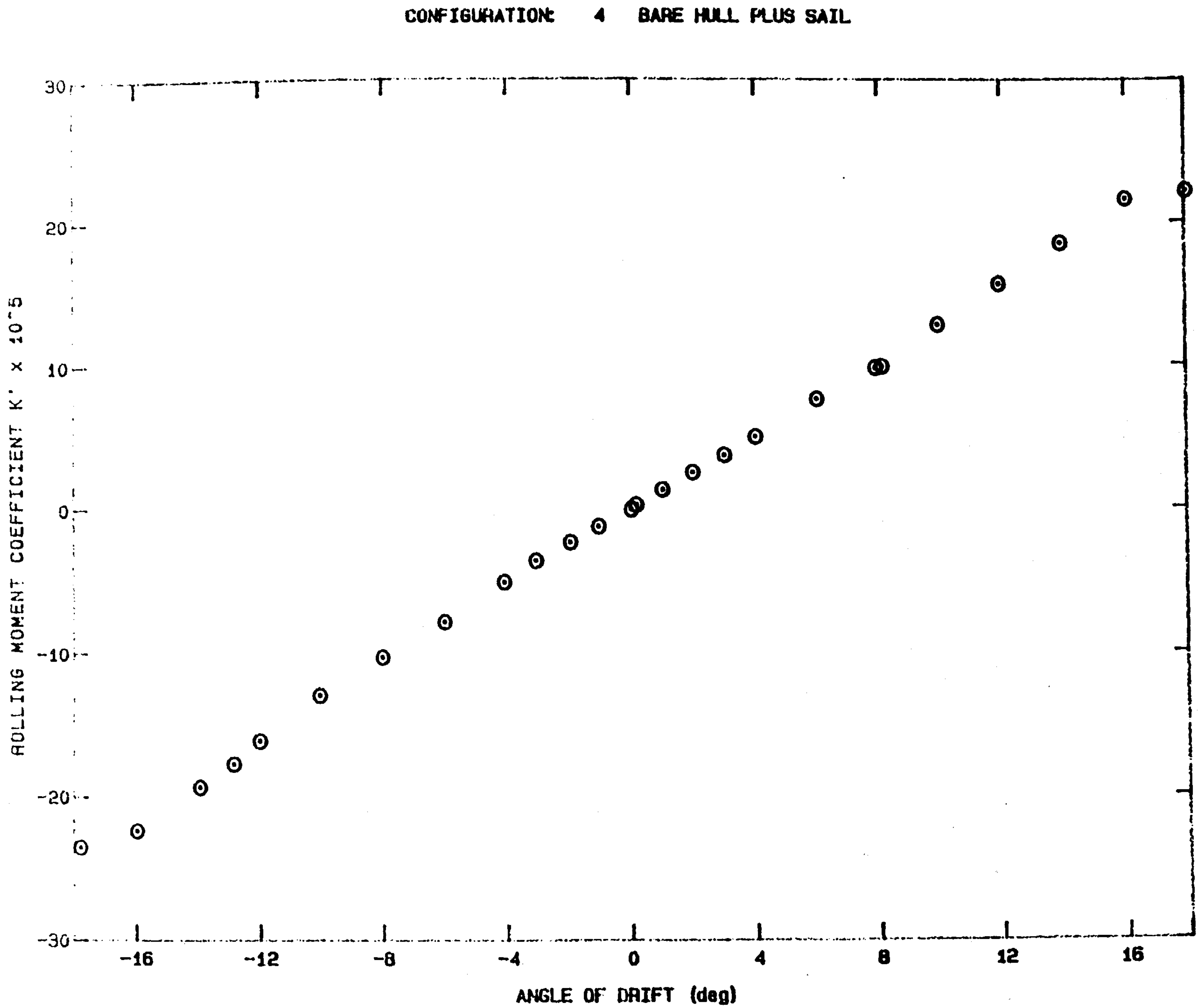

Fig. 51. Effect of angle of drift on the rolling moment coefficient for Configuration 4.

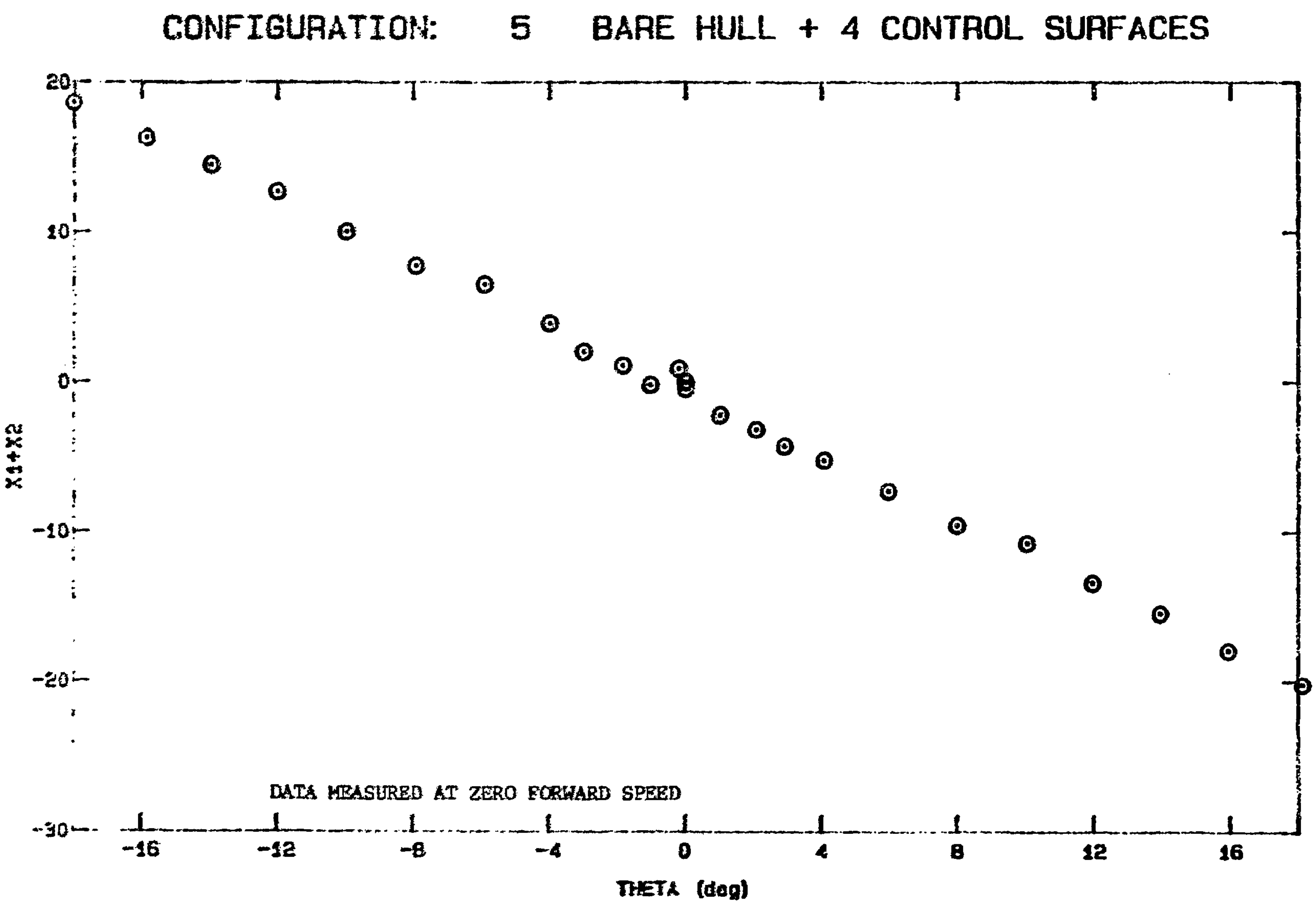

Fig. 52. Effect of tilt table angle on the longitudinal force at standstill for use in correcting the underway longitudinal force data and in determining the weight of the model in water for Configuration 5.

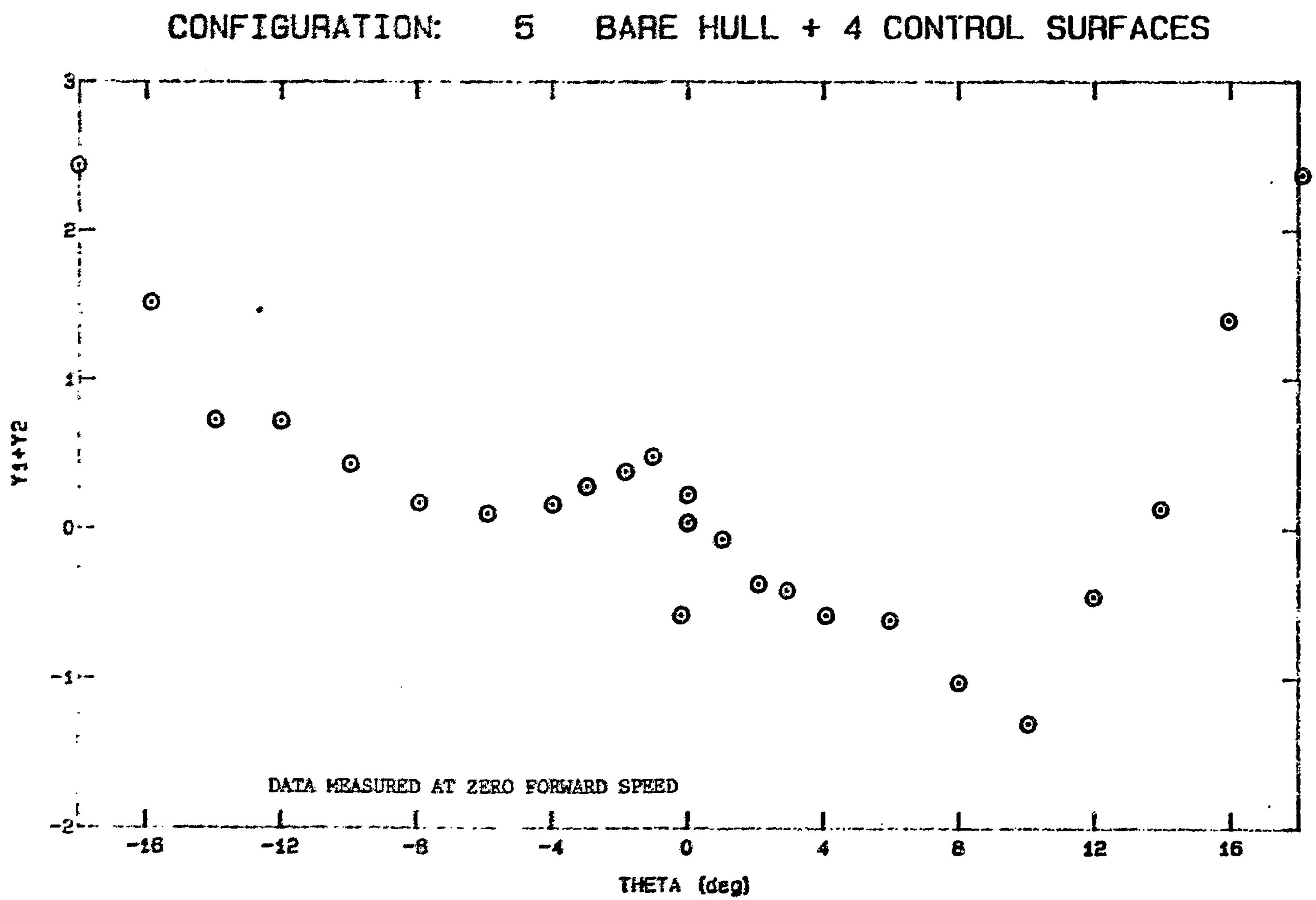

Fig. 53. Effect of tilt table angle on the lateral force at standstill for use in correcting the underway lateral force data for Configuration 5.

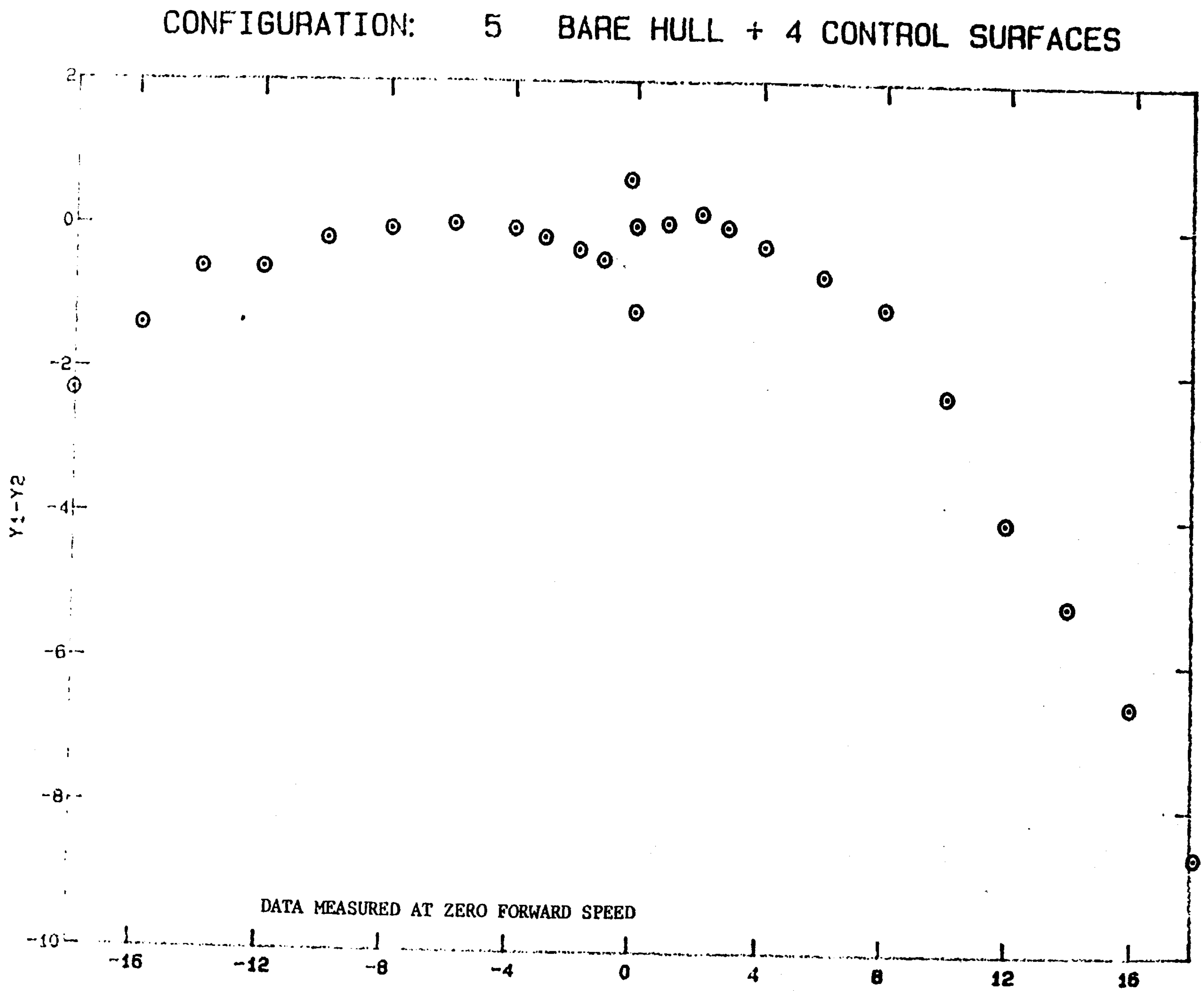

Fig. 54. Effect of tilt table angle on the difference between the forward and aft lateral force data for use in correcting the underway yawing moment data and in determining the longitudinal location of the center of gravity for Configuration 5.

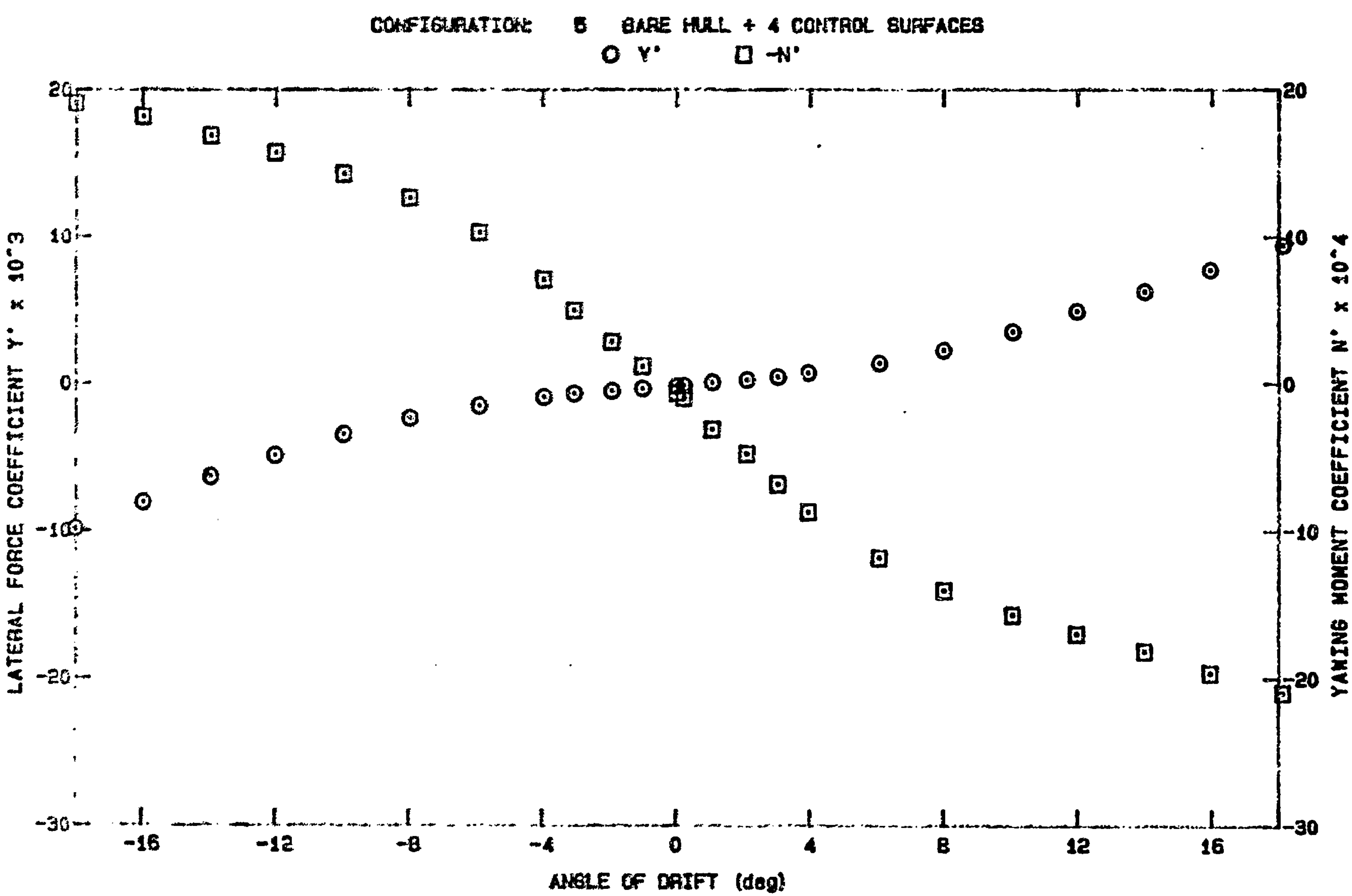

Fig. 55. Effect of angle of drift on the lateral force and yawing moment coefficients for Configuration 5.

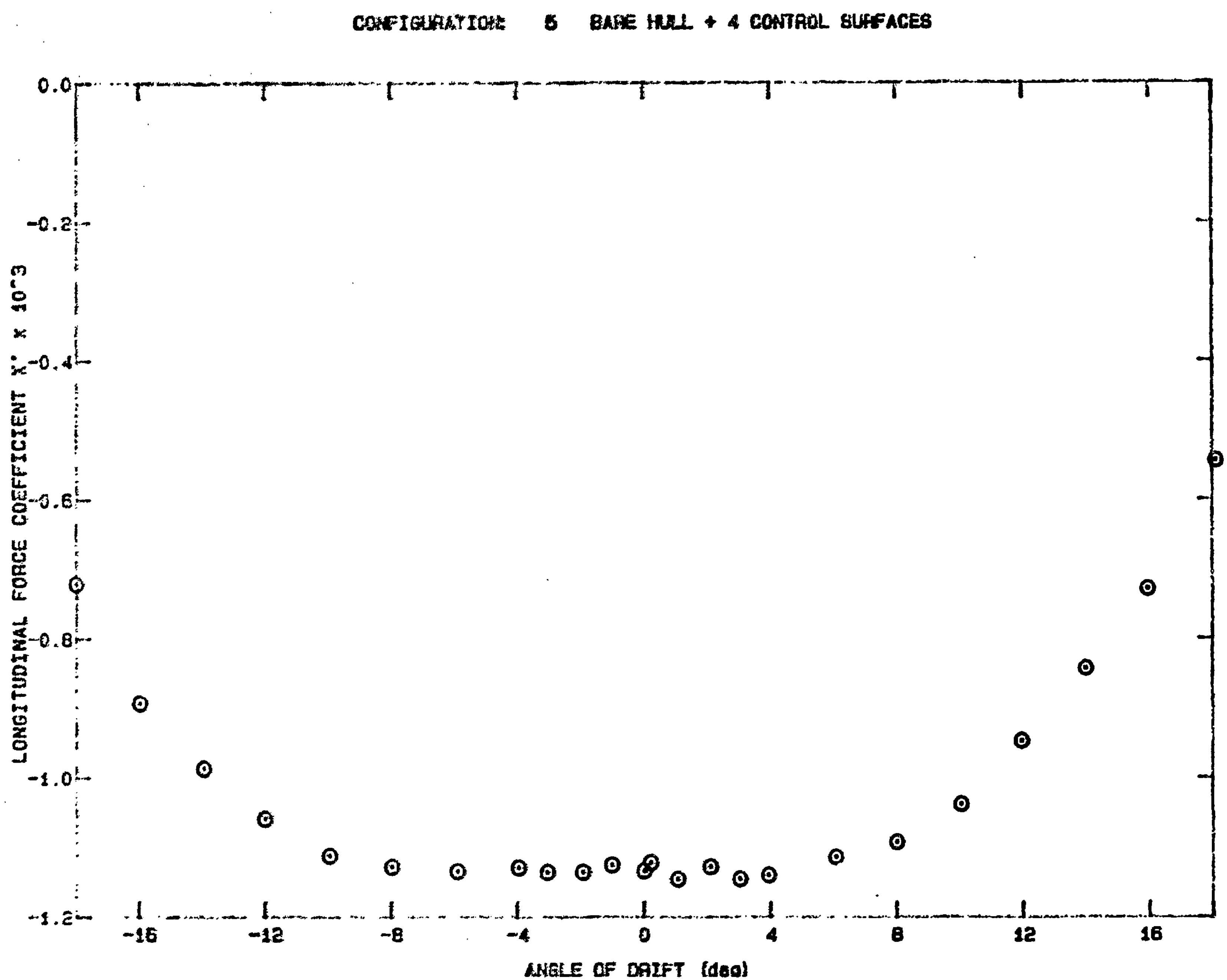

Fig. 56. Effect of angle of drift on the longitudinal force coefficient for Configurations 5.

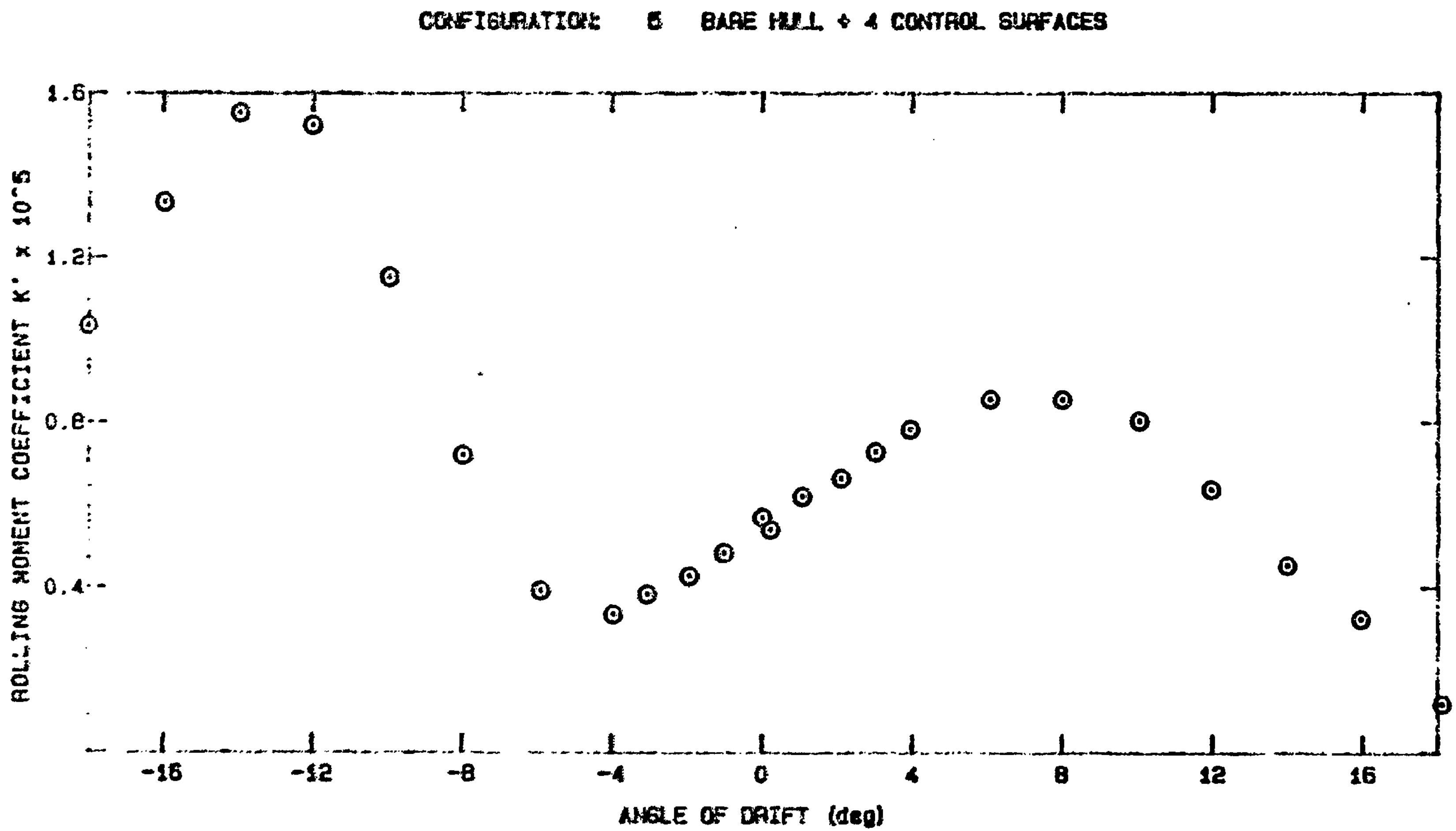

Fig. 57. Effect of angle of drift on the rolling moment coefficient for Configuration 5.

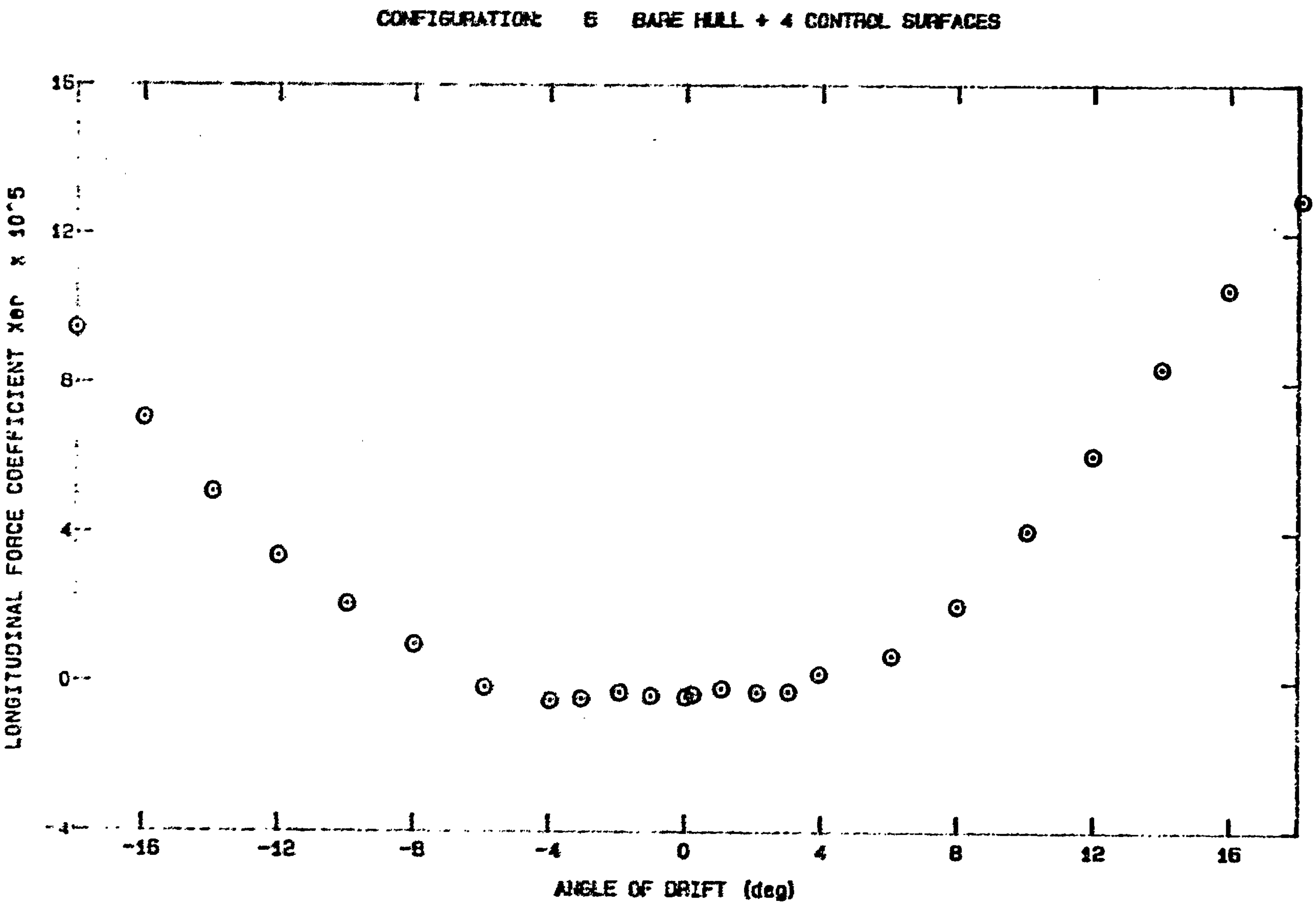

Fig. 58. Effect of angle of drift on the longitudinal force coefficient measured on one rudder for Configuration 5.

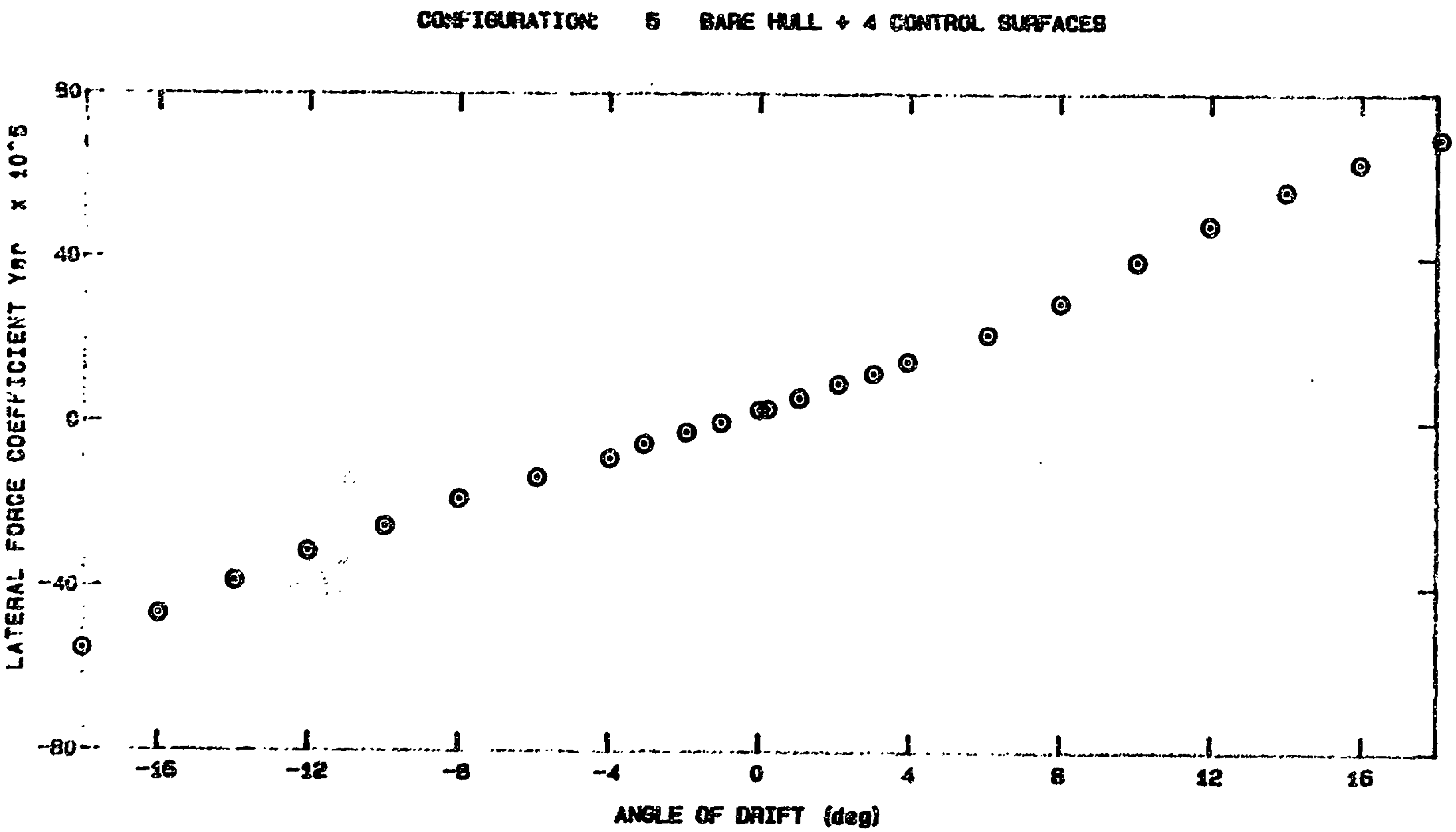

Fig. 59. Effect of angle of drift on the lateral force coefficient measured on one rudder for Configuration 5.

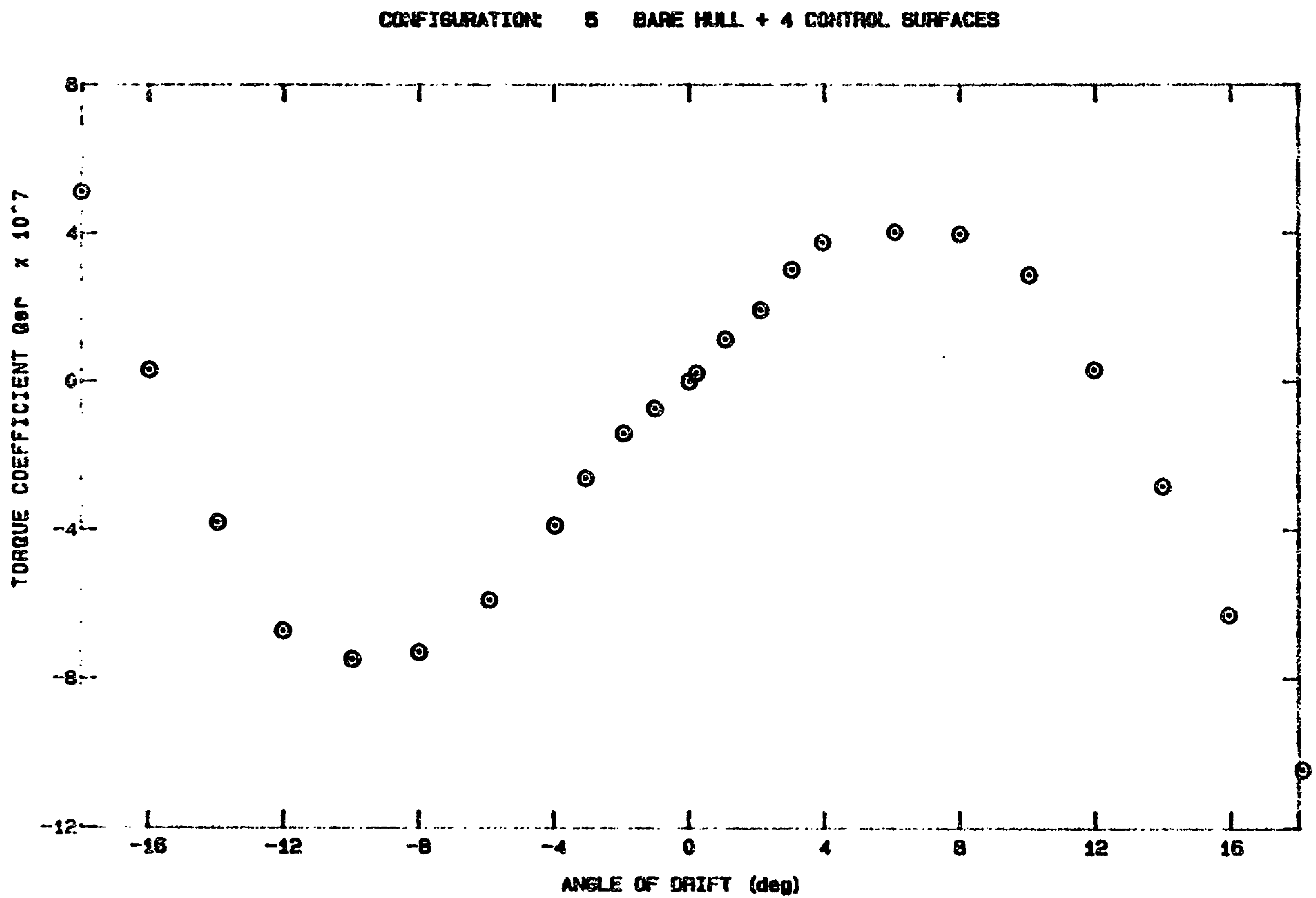

Fig. 60. Effect of angle of drift on the hydrodynamic torque coefficient measured on the stock of one rudder for Configuration 5.

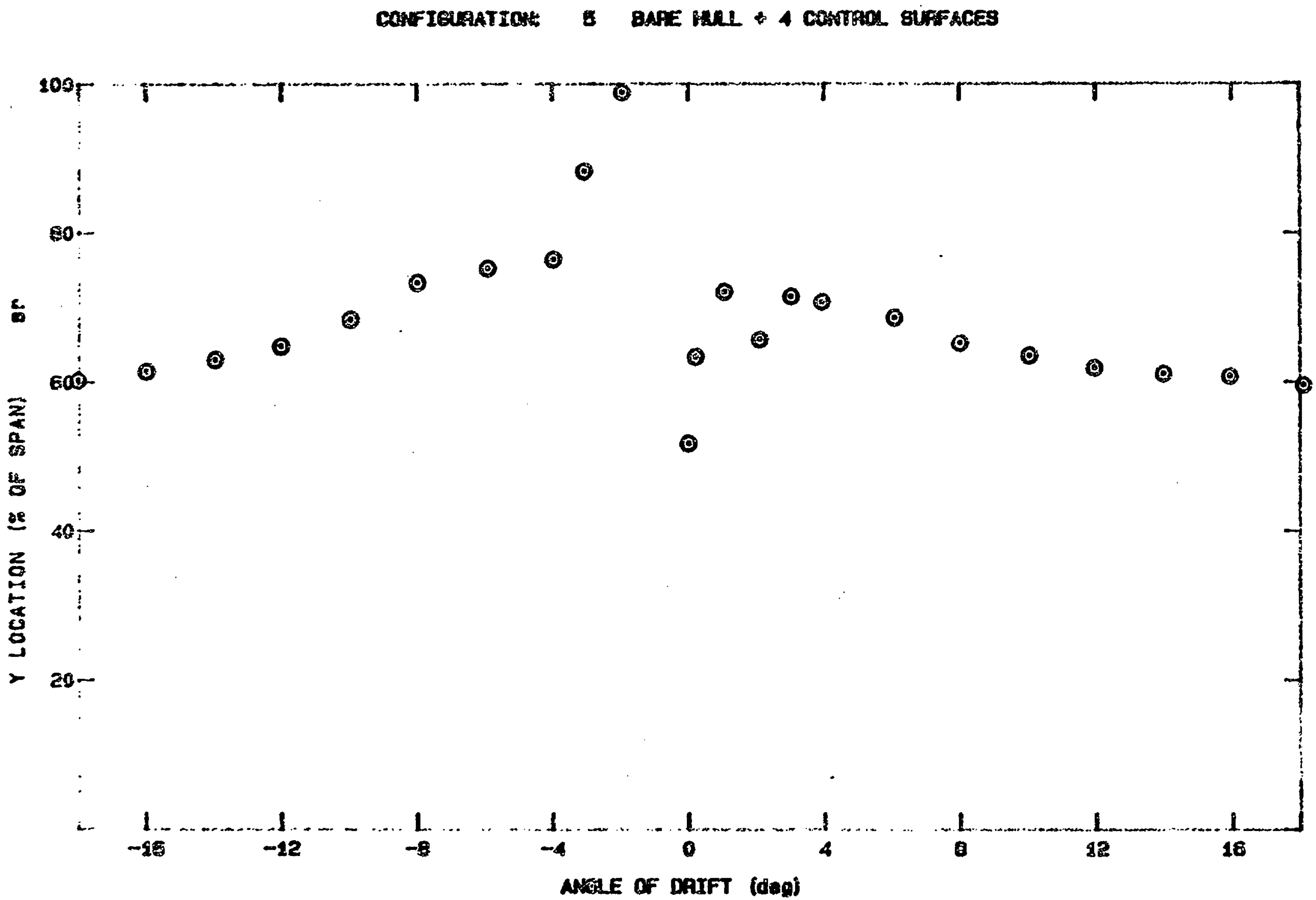

Fig. 61. Effect of angle of drift on the percent spanwise location of the center of pressure measured on one rudder for Configuration 5.

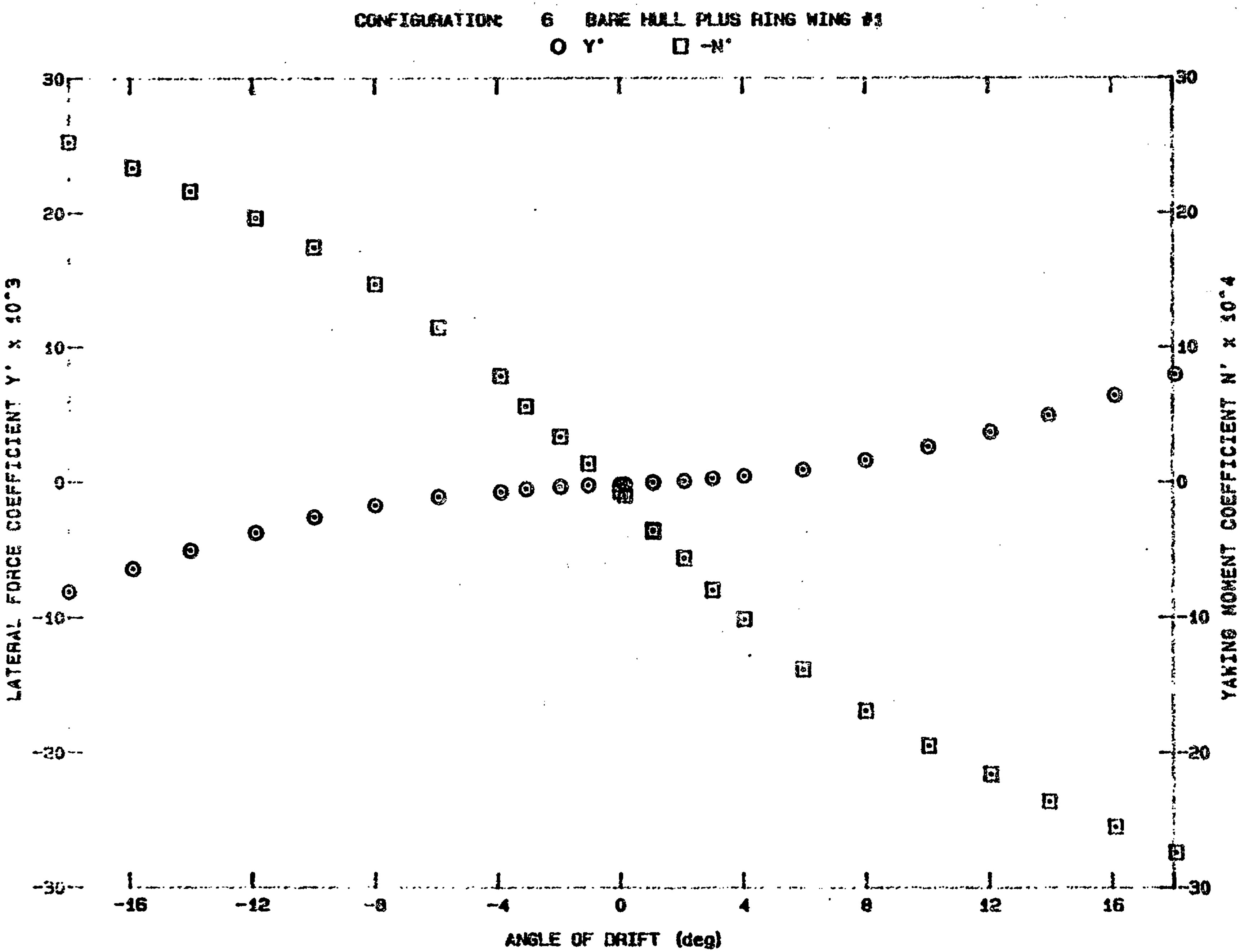

Fig. 62. Effect of angle of drift on the lateral force and yawing moment coefficients for Configuration 6.

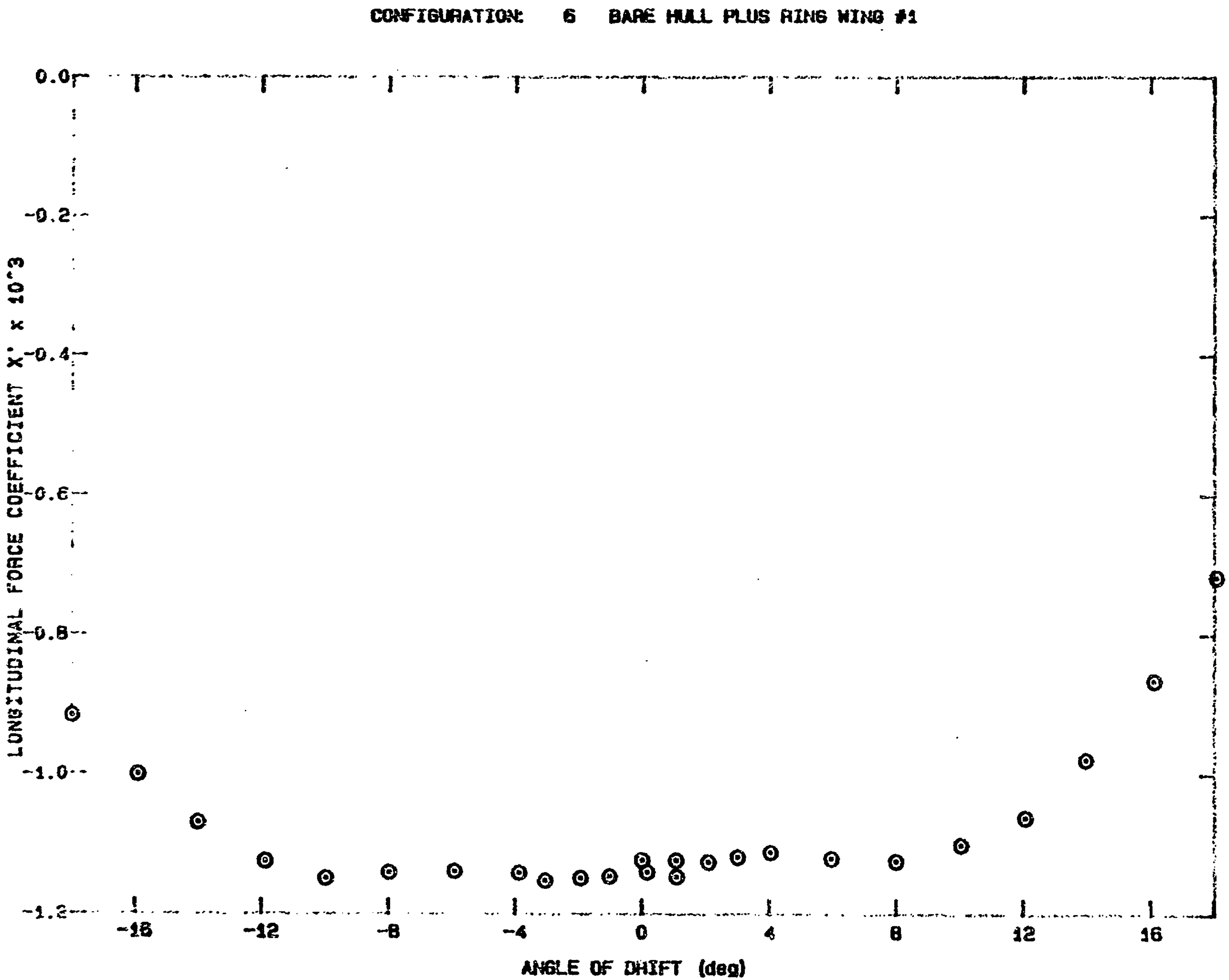

Fig. 63. Effect of angle of drift on the longitudinal force coefficient for Configurations 6.

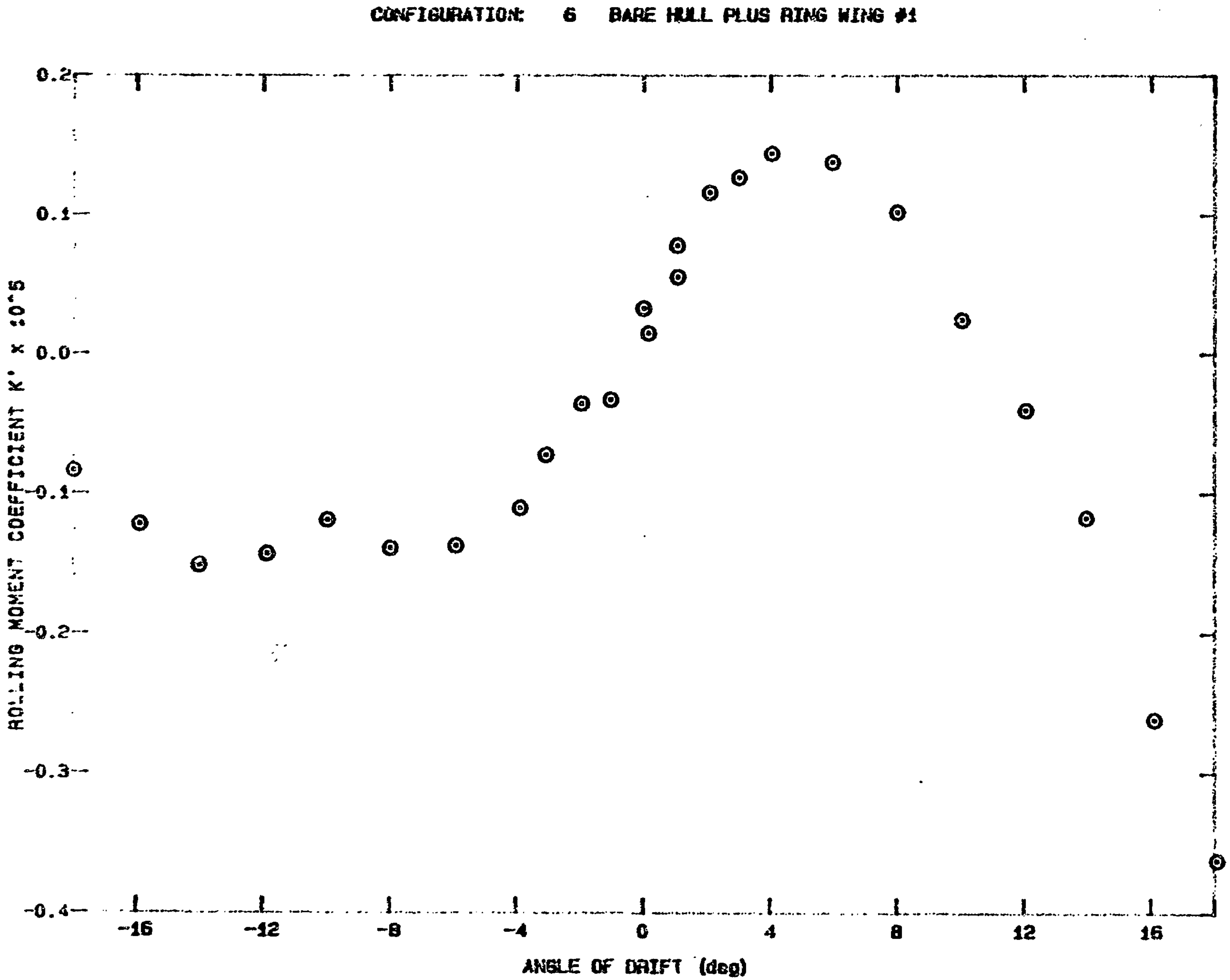

Fig. 64. Effect of angle of drift on the rolling moment coefficient for Configuration 6.

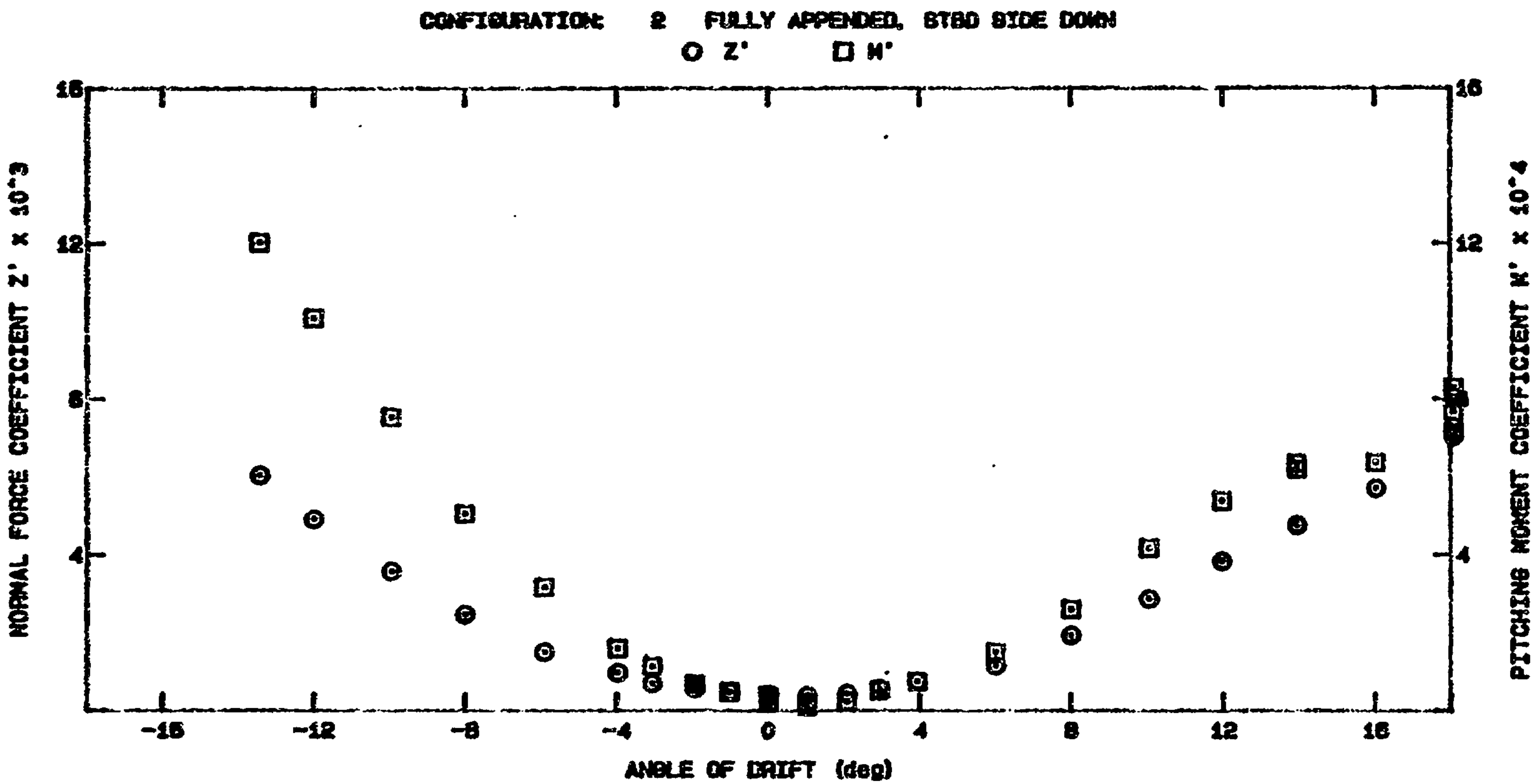

Fig. 65. Effect of angle of drift on the out-of-plane normal force and pitching moment for Configuration 2.

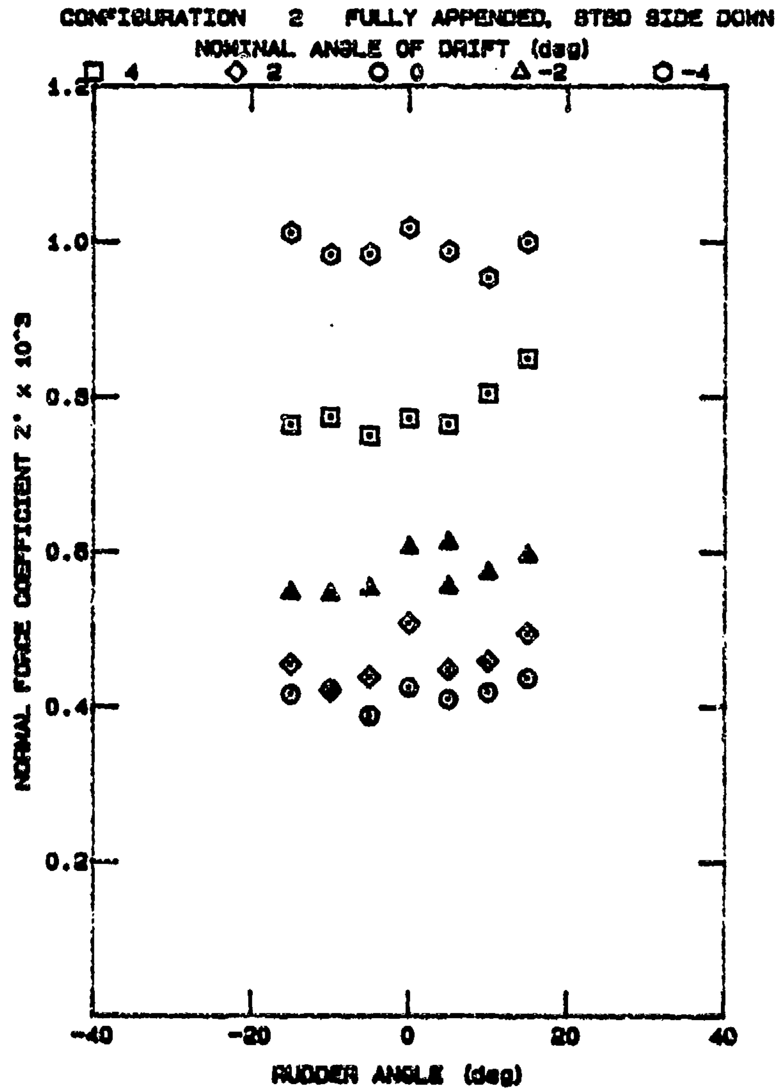

Fig. 66. Effect of rudder angle on the out-of-plane normal force for Configuration 2.

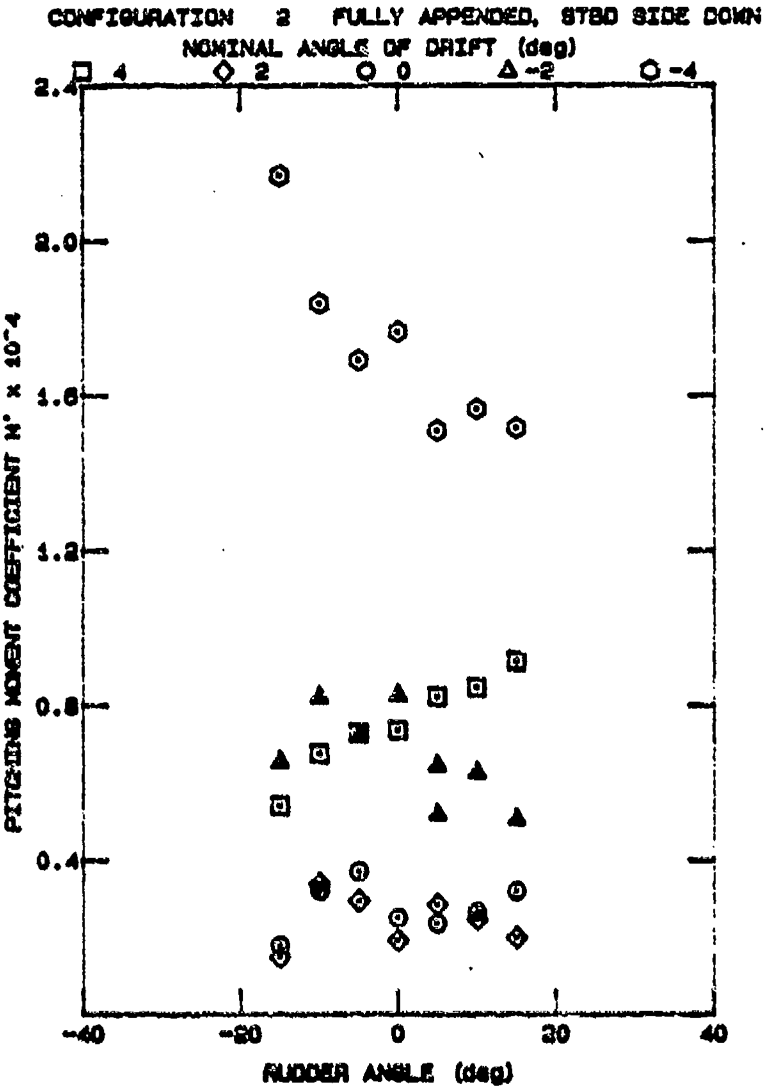

Fig. 67. Effect of rudder angle on the out-of-plane pitching moment for Configuration 2.

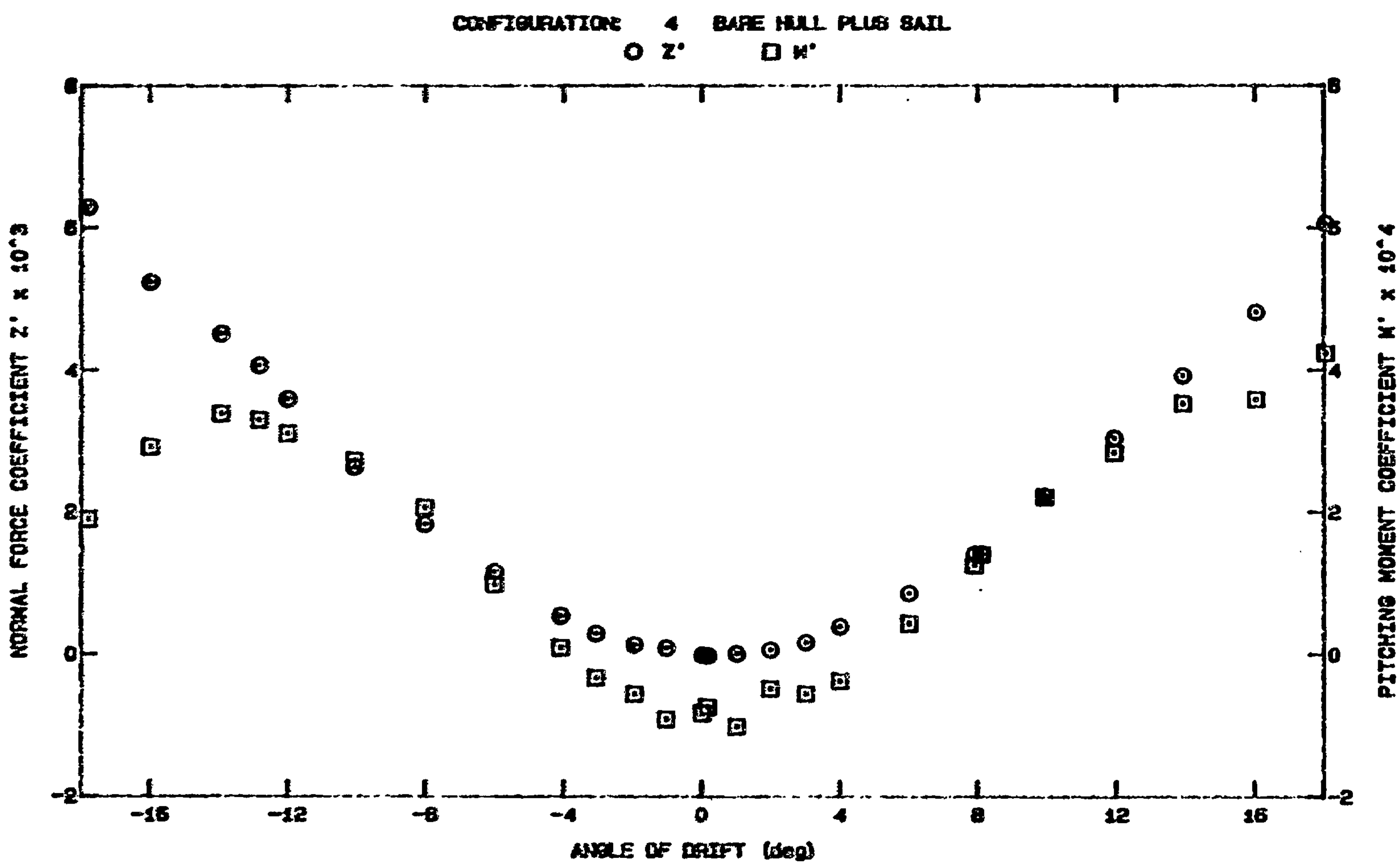

Fig. 68. Effect of angle of drift on the out-of-plane normal force and pitching moment for Configuration 4.

APPENDIX B

RESULTS OF THE CAPTIVE-MODEL EXPERIMENTS IN TABULAR FORM

MODEL MODEL 5470 CONFIGURATION 1
VERTICAL PLANE
PORT STERNPL

POINT	STERN PLANE ANGLE	ATTACK ANGLE	TORQUE'	X'	X% SPAN	Z'	Z% SPAN	TIME	DATE
1	0.0	0.00	2.586E-08	-3.932E-06	-183.57	-2.066E-05	37.95	22:24:51	1/17/90
2	0.0	1.07	1.599E-07	-4.230E-06	-186.70	-4.838E-05	72.57	22:25:10	1/17/90
3	0.0	2.09	2.517E-07	-3.945E-06	-223.51	-6.629E-05	77.32	22:25:25	1/17/90
4	0.0	3.00	3.653E-07	-7.309E-07	-1358.97	-1.002E-04	73.85	22:25:40	1/17/90
5	0.0	4.05	4.471E-07	-4.791E-07	-2457.87	-1.163E-04	77.05	22:25:52	1/17/90
6	0.0	5.97	4.050E-07	5.641E-06	296.05	-1.940E-04	67.69	22:34:10	1/17/90
7	0.0	8.00	4.651E-07	1.927E-05	132.85	-2.558E-04	68.19	22:34:26	1/17/90
8	0.0	10.05	3.851E-07	3.721E-05	102.76	-3.610E-04	63.57	22:34:41	1/17/90
9	0.0	11.96	1.831E-07	5.776E-05	92.42	-4.550E-04	60.68	22:34:56	1/17/90
10	0.0	13.94	-1.287E-07	7.838E-05	88.47	-5.280E-04	61.63	22:42:22	1/17/90
11	0.0	16.02	-5.058E-07	9.949E-05	85.61	-5.969E-04	60.75	22:42:40	1/17/90
12	0.0	18.09	-9.791E-07	1.236E-04	82.73	-6.543E-04	59.99	22:42:59	1/17/90
13	0.0	0.00	3.733E-08	-4.086E-06	-182.90	-1.702E-05	37.30	22:51:29	1/17/90
14	0.0	-1.04	-5.981E-08	-4.569E-06	-167.84	1.518E-05	78.72	22:51:42	1/17/90
15	0.0	-1.85	-1.587E-07	-5.243E-06	-157.43	3.147E-05	86.16	22:51:55	1/17/90
16	0.0	-3.07	-2.844E-07	-3.897E-06	-230.49	5.325E-05	90.72	22:52:12	1/17/90
17	0.0	-3.89	-4.001E-07	-1.664E-06	-631.40	8.695E-05	78.69	22:52:34	1/17/90
18	0.0	-6.02	-5.222E-07	6.550E-07	2207.76	1.408E-04	74.96	22:59:56	1/17/90
19	0.0	-8.04	-6.613E-07	9.835E-06	217.08	1.927E-04	71.98	23: 0:13	1/17/90
20	0.0	-9.98	-6.439E-07	2.353E-05	129.42	2.602E-04	67.56	23: 0:32	1/17/90
21	0.0	-12.02	-5.700E-07	3.832E-05	104.66	3.192E-04	64.63	23: 0:48	1/17/90
22	0.0	-13.97	-2.798E-07	5.672E-05	94.41	3.983E-04	63.32	23: 8:54	1/17/90
23	0.0	-15.99	8.946E-08	7.213E-05	90.78	4.563E-04	62.22	23: 9:12	1/17/90
24	0.0	-17.62	4.358E-07	8.990E-05	86.76	5.162E-04	60.86	23: 9:29	1/17/90
25	0.0	0.00	3.021E-08	-3.751E-06	-194.72	-2.213E-05	37.26	9:33:53	1/18/90
26	0.0	2.00	2.283E-07	-4.185E-06	-208.71	-5.857E-05	79.59	9:34: 9	1/18/90
27	0.0	4.03	4.271E-07	7.231E-07	1551.28	-1.182E-04	73.78	9:34:22	1/18/90
28	0.0	-1.97	-1.924E-07	-5.297E-06	-157.50	3.412E-05	88.13	9:34:48	1/18/90
29	0.0	-4.01	-4.173E-07	-2.334E-06	-440.99	8.572E-05	79.20	9:35: 5	1/18/90
30	5.0	-4.10	-7.620E-07	-5.093E-06	-73.84	-9.709E-05	32.18	10:59:38	1/18/90
31	5.0	-2.01	-4.798E-07	3.863E-08	16713.82	-1.417E-04	54.12	10:59:59	1/18/90
32	5.0	0.11	-3.003E-07	4.889E-06	211.59	-1.906E-04	60.80	11: 0:19	1/18/90
33	5.0	2.05	-1.595E-07	1.276E-05	125.09	-2.447E-04	63.71	11: 0:36	1/18/90
34	5.0	3.99	-1.320E-07	2.227E-05	111.62	-3.157E-04	62.99	11: 0:55	1/18/90
35	10.0	-4.10	-9.891E-07	5.893E-06	130.95	-2.420E-04	53.92	11:32: 5	1/18/90
36	10.0	-2.00	-8.218E-07	1.380E-05	110.08	-2.873E-04	59.51	11:32:21	1/18/90
37	10.0	0.04	-7.951E-07	2.501E-05	96.45	-3.561E-04	61.60	11:32:41	1/18/90
38	10.0	2.06	-8.199E-07	3.667E-05	91.81	-4.163E-04	62.69	11:33: 0	1/18/90
39	10.0	3.99	-9.537E-07	5.496E-05	91.26	-4.992E-04	62.52	11:33:14	1/18/90
40	15.0	-4.10	-1.280E-06	2.077E-05	97.06	-3.974E-04	56.17	13:19:49	1/18/90

MODEL MODEL 5470 CONFIGURATION 1
VERTICAL PLANE
PORT STERNPL

POINT	STERN PLANE ANGLE	ATTACK ANGLE	TORQUE'	X'	X% SPAN	Z'	Z% SPAN	TIME	DATE
41	15.0	-2.05	-1.358E-C6	3.456E-05	93.61	-4.591E-04	59.82	13:20: 9	1/18/90
42	15.0	0.14	-1.518E-06	4.952E-05	90.16	-5.179E-04	61.39	13:20:27	1/18/90
43	15.0	2.09	-1.730E-06	6.995E-05	88.06	-6.014E-04	61.50	13:20:46	1/18/90
44	15.0	3.94	-2.071E-06	9.253E-05	86.50	-6.814E-04	61.77	13:21: 5	1/18/90
45	-5.0	-1.08	2.336E-07	4.227E-06	257.80	1.743E-04	61.99	13:59: 1	1/18/90
46	-5.0	-4.04	2.838E-08	1.662E-05	134.54	2.667E-04	64.64	13:59:19	1/18/90
47	-5.0	-2.06	1.347E-07	8.941E-06	162.12	2.004E-04	64.00	13:59:40	1/18/90
48	-5.0	0.19	3.364E-07	9.508E-07	866.55	1.425E-04	58.61	14: 0: 2	1/18/90
49	-5.0	2.06	5.383E-07	-1.339E-06	-457.18	8.288E-05	51.31	14: 0:21	1/18/90
50	-5.0	-0.04	3.104E-07	1.294E-06	701.99	1.395E-04	61.87	14:11:59	1/18/90
51	-5.0	2.07	5.348E-07	-1.444E-06	-427.72	8.227E-05	51.41	14:12:19	1/18/90
52	-5.0	4.01	7.782E-07	-6.477E-06	-66.47	3.156E-05	15.68	14:12:36	1/18/90
53	-10.0	-3.98	8.021E-07	4.666E-05	92.65	4.434E-04	63.95	14:36: 9	1/18/90
54	-10.0	-1.96	6.989E-07	2.932E-05	96.33	3.667E-04	62.63	14:36:28	1/18/90
55	-10.0	0.21	7.221E-07	1.954E-05	92.30	3.060E-04	60.24	14:36:47	1/18/90
56	-10.0	1.91	7.928E-07	1.023E-05	109.25	2.527E-04	57.47	14:37:10	1/18/90
57	-10.0	4.09	1.043E-06	4.487E-06	95.54	2.019E-04	50.58	14:37:29	1/18/90
58	-15.0	-1.84	1.487E-06	6.076E-05	82.81	5.428E-04	61.76	15: 8:59	1/18/90
59	-15.0	-4.00	1.707E-06	8.304E-05	81.98	6.193E-04	62.42	15: 9:16	1/18/90
60	-15.0	-1.96	1.490E-06	6.061E-05	82.52	5.406E-04	61.77	15: 9:33	1/18/90
61	-15.0	-0.06	1.396E-06	4.691E-05	81.54	4.781E-04	62.00	15: 9:50	1/18/90
62	-15.0	2.10	1.279E-06	3.287E-05	77.63	4.122E-04	59.33	15:10: 9	1/18/90
63	-15.0	0.03	1.391E-06	4.738E-05	80.71	4.778E-04	61.93	15:20:27	1/18/90
64	-15.0	1.98	1.277E-06	3.301E-05	77.81	4.146E-04	59.27	15:20:43	1/18/90
65	-15.0	4.00	1.209E-06	2.262E-05	72.75	3.440E-04	56.84	15:21: 2	1/18/90
66	-15.0	4.00	1.217E-06	2.356E-05	71.81	3.456E-04	56.80	15:21:14	1/18/90

MODEL MODEL 5470 CONFIGURATION 2
HORIZONTAL PLANE
UPPER RUDDER

POINT	STERN PLANE ANGLE	DRIFT ANGLE	TORQUE'	X'	X% SPAN	Y'	Y% SPAN	TIME	DATE
67	0.0	0.00	-7.997E-08	-3.066E-06	-247.43	3.571E-05	36.89	15: 0:33	1/19/90
68	0.0	1.03	-4.179E-08	-2.947E-06	-268.41	3.549E-05	60.26	15: 0:49	1/19/90
69	0.0	2.08	-1.298E-07	-2.593E-06	-305.66	5.034E-05	63.47	15: 1: 7	1/19/90
70	0.0	2.94	-9.376E-08	-1.573E-06	-552.28	5.918E-05	65.94	15: 1:20	1/19/90
71	0.0	3.93	2.490E-07	-1.623E-06	-519.80	5.253E-05	76.91	15: 1:40	1/19/90
72	0.0	6.01	4.880E-07	-9.335E-07	-1019.29	8.852E-05	77.49	15:12:15	1/19/90
73	0.0	8.00	4.886E-07	7.194E-06	210.27	1.503E-04	72.54	15:12:32	1/19/90
74	0.0	10.05	6.657E-07	1.367E-05	159.45	2.060E-04	69.75	15:12:48	1/19/90
75	0.0	11.97	6.748E-07	2.478E-05	124.84	2.703E-04	67.42	15:13: 4	1/19/90
76	0.0	13.94	4.955E-07	3.953E-05	109.53	3.622E-04	64.08	15:13:23	1/19/90
77	0.0	13.95	4.789E-07	4.094E-05	108.52	3.673E-04	64.17	15:23:55	1/19/90
78	0.0	16.03	2.376E-08	6.391E-05	97.29	4.780E-04	62.27	15:24:13	1/19/90
79	0.0	18.09	-4.649E-07	8.813E-05	87.23	5.579E-04	60.86	15:24:31	1/19/90
80	0.0	18.07	-5.528E-07	8.793E-05	89.09	5.805E-04	60.46	15:34:57	1/19/90
81	0.0	18.08	-5.127E-07	8.604E-05	89.62	5.688E-04	60.53	15:35:27	1/19/90
82	0.0	0.00	-7.324E-08	-3.043E-06	-252.02	3.386E-05	37.69	16:27:54	1/19/90
83	0.0	-1.04	-5.908E-08	-3.202E-06	-234.69	1.146E-05	32.02	16:28: 7	1/19/90
84	0.0	-1.95	8.794E-08	-3.427E-06	-226.31	-4.498E-06	108.81	16:28:25	1/19/90
85	0.0	-3.07	5.607E-08	-2.580E-06	-310.29	-2.136E-05	74.01	16:28:42	1/19/90
86	0.0	-3.98	-2.676E-07	-2.713E-06	-253.19	-1.568E-05	133.73	16:28:56	1/19/90
87	0.0	-5.92	-4.630E-07	-3.993E-06	-178.96	-3.934E-05	103.75	16:39:18	1/19/90
88	0.0	-8.01	-6.691E-07	-1.165E-06	-934.31	-7.632E-05	92.23	16:39:35	1/19/90
89	0.0	-9.97	-8.354E-07	2.876E-06	579.33	-1.236E-04	78.14	16:39:51	1/19/90
90	0.0	-12.02	-8.737E-07	1.202E-05	203.51	-1.857E-04	70.60	16:40: 9	1/19/90
91	0.0	-13.44	-7.509E-07	2.244E-05	143.92	-2.496E-04	66.30	16:52:20	1/19/90
92	0.0	-0.00	-7.970E-08	-2.977E-06	-258.50	3.523E-05	35.99	17:18:32	1/19/90
93	0.0	2.11	-1.248E-07	-2.281E-06	-348.18	5.131E-05	63.99	17:18:52	1/19/90
94	0.0	3.92	2.411E-07	-1.578E-06	-542.42	5.248E-05	76.73	17:19:11	1/19/90
95	0.0	-2.05	1.006E-07	-3.317E-06	-235.81	-6.521E-06	95.28	17:19:36	1/19/90
96	0.0	-4.03	-2.777E-07	-2.666E-06	-256.02	-1.685E-05	127.56	17:19:52	1/19/90
97	5.0	0.16	-3.920E-07	5.659E-06	182.39	1.909E-04	59.62	17:56:20	1/19/90
98	5.0	2.08	-4.843E-07	8.642E-06	136.91	2.066E-04	61.42	17:56:38	1/19/90
99	5.0	4.09	-1.320E-07	1.074E-05	139.33	2.018E-04	63.65	17:56:57	1/19/90
100	5.0	-2.05	-3.148E-07	5.867E-06	148.53	1.538E-04	59.66	17:57:26	1/19/90
101	5.0	-1.84	-3.408E-07	6.433E-06	138.65	1.628E-04	58.93	18: 6:49	1/19/90
102	5.0	-3.99	-6.037E-07	2.629E-06	227.47	1.428E-04	53.57	18: 7: 7	1/19/90
103	10.0	0.11	-7.809E-07	2.439E-05	95.66	3.574E-04	59.08	18:22: 6	1/19/90
104	10.0	2.08	-9.041E-07	2.777E-05	98.95	3.597E-04	61.55	18:22:25	1/19/90
105	10.0	4.09	-6.404E-07	3.165E-05	101.59	3.433E-04	63.88	18:22:44	1/19/90
106	10.0	-2.00	-7.660E-07	2.168E-05	93.55	3.276E-04	59.40	18:23:10	1/19/90

MODEL MODEL 5470 CONFIGURATION 2
HORIZONTAL PLANE
UPPER RUDDER

POINT	STERN PLANE ANGLE	DRIFT ANGLE	TORQUE'	X'	X% SPAN	Y'	Y% SPAN	TIME	DATE
107	10.0	-4.09	-9.875E-07	1.716E-05	81.44	2.908E-04	57.04	18:23:28	1/19/90
108	15.0	0.21	-1.497E-06	5.258E-05	86.85	5.208E-04	60.65	19: 0:15	1/19/90
109	15.0	2.03	-1.606E-06	5.640E-05	89.63	5.151E-04	61.36	19: 0:31	1/19/90
110	15.0	4.09	-1.625E-06	6.167E-05	91.78	5.119E-04	62.38	19: 0:49	1/19/90
111	15.0	-2.05	-1.501E-06	4.941E-05	83.38	4.980E-04	60.20	19: 1:18	1/19/90
112	15.0	-3.99	-1.465E-06	4.031E-05	78.95	4.286E-04	59.42	19: 1:34	1/19/90

MODEL MODEL 5470 CONFIGURATION 2
HORIZONTAL PLANE
UPPER RUDDER

POINT	RUDDER ANGLE	DRIFT ANGLE	TORQUE'	X'	X% SPAN	Y'	Y% SPAN	TIME	DATE
113	-5.0	-0.00	1.937E-07	3.457E-06	294.16	-1.431E-04	58.87	19:13:50	1/19/90
114	-5.0	2.09	2.073E-07	2.424E-06	346.83	-1.072E-04	59.92	19:14: 9	1/19/90
115	-5.0	4.09	5.502E-07	9.227E-07	683.38	-9.294E-05	50.19	19:14:27	1/19/90
116	-5.0	-2.05	4.236E-07	4.398E-06	243.35	-1.722E-04	60.11	19:14:55	1/19/90
117	-5.0	-4.10	4.905E-08	6.383E-06	206.03	-1.664E-04	65.07	19:15:13	1/19/90
118	-10.0	-0.00	5.863E-07	2.042E-05	97.45	-3.122E-04	59.86	19:28: 3	1/19/90
119	-10.0	2.09	6.143E-07	2.034E-05	83.73	-2.821E-04	59.24	19:28:23	1/19/90
120	-10.0	4.09	8.785E-07	1.555E-05	71.99	-2.370E-04	57.35	19:28:41	1/19/90
121	-10.0	-2.05	8.642E-07	2.370E-05	97.29	-3.317E-04	61.12	19:29:11	1/19/90
122	-10.0	-3.99	6.161E-07	2.799E-05	99.02	-3.325E-04	62.47	19:29:29	1/19/90
123	-15.0	0.00	1.327E-06	4.771E-05	81.65	-4.866E-04	61.04	19:43: 9	1/19/90
124	-15.0	2.11	1.285E-06	4.372E-05	79.60	-4.530E-04	60.20	19:43:27	1/19/90
125	-15.0	3.93	1.265E-06	3.395E-05	75.66	-3.882E-04	58.01	19:43:45	1/19/90
126	-15.0	-2.05	1.493E-06	5.102E-05	85.51	-4.966E-04	61.23	19:44:16	1/19/90
127	-15.0	-4.10	1.459E-06	5.547E-05	88.57	-4.926E-04	61.88	19:44:34	1/19/90

MODEL MODEL 5470 CONFIGURATION 5

HORIZONTAL PLANE

UPPER RUDDER

POINT	RUDDER ANGLE	DRIFT ANGLE	TORQUE'	X'	X% SPAN	Y'	Y% SPAN	TIME	DATE
128	0.0	0.00	5.305E-11	-3.944E-06	-141.38	3.152E-05	52.09	13:54:24	1/20/90
129	0.0	1.06	1.135E-07	-1.702E-06	-365.05	5.990E-05	72.59	13:54:42	1/20/90
130	0.0	2.11	1.926E-07	-2.608E-06	-255.68	9.479E-05	66.12	13:54:57	1/20/90
131	0.0	3.03	3.011E-07	-2.473E-06	-362.03	1.195E-04	71.95	13:55:10	1/20/90
132	0.0	3.94	3.743E-07	2.354E-06	461.38	1.493E-04	71.18	13:55:26	1/20/90
133	0.0	6.08	4.026E-07	7.147E-06	238.00	2.140E-04	69.05	14: 5:31	1/20/90
134	0.0	8.00	3.968E-07	2.045E-05	127.15	2.899E-04	65.63	14: 5:47	1/20/90
135	0.0	10.05	2.868E-07	4.050E-05	98.64	3.902E-04	63.92	14: 6: 4	1/20/90
136	0.0	11.97	3.130E-08	6.063E-05	91.11	4.800E-04	62.30	14: 6:23	1/20/90
137	0.0	13.99	-2.831E-07	8.405E-05	86.43	5.631E-04	61.49	14: 6:40	1/20/90
138	0.0	15.95	-6.289E-07	1.051E-04	84.14	6.313E-04	61.16	14:16:38	1/20/90
139	0.0	18.11	-1.043E-06	1.291E-04	81.93	6.912E-04	59.92	14:16:57	1/20/90
140	0.0	0.20	2.148E-08	-3.263E-06	-176.03	3.242E-05	63.81	14:29:14	1/20/90
141	0.0	-1.03	-7.322E-08	-3.579E-06	-160.34	-2.508E-07	1346.14	14:29:27	1/20/90
142	0.0	-1.95	-1.401E-07	-2.705E-06	-227.10	-2.382E-05	99.48	14:29:42	1/20/90
143	0.0	-3.07	-2.608E-07	-4.308E-06	-162.95	-5.229E-05	88.83	14:29:58	1/20/90
144	0.0	-3.97	-3.881E-07	-4.857E-06	-180.93	-8.778E-05	76.96	14:30: 9	1/20/90
145	0.0	-5.92	-5.892E-07	-1.307E-06	-981.65	-1.348E-04	75.72	14:30:27	1/20/90
146	0.0	-8.00	-7.299E-07	9.920E-06	202.93	-1.870E-04	73.80	14:39:56	1/20/90
147	0.0	-9.98	-7.485E-07	2.080E-05	137.39	-2.548E-04	68.85	14:40:11	1/20/90
148	0.0	-12.02	-6.722E-07	3.364E-05	113.26	-3.154E-04	65.19	14:40:26	1/20/90
149	0.0	-13.96	-3.801E-07	5.087E-05	97.84	-3.871E-04	63.42	14:40:41	1/20/90
150	0.0	-15.99	3.027E-08	7.057E-05	91.67	-4.683E-04	61.83	14:41: 2	1/20/90
151	0.0	-18.01	5.109E-07	9.458E-05	86.60	-5.530E-04	60.59	14:48:25	1/20/90

MODEL MODEL 5470 CONFIGURATION 1

VERTICAL PLANE

POINT	STERN PLANE ANGLE	ATTACK ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
1	0.0	0.00	-1.302E-03	5.293E-04	1.865E-04	9.333E-06	2.640E-05	9.720E-05	-0.	6.50
2	0.0	1.07	-1.303E-03	4.355E-04	-1.054E-04	9.038E-06	2.736E-05	3.195E-04	-0.	6.50
3	0.0	2.09	-1.292E-03	4.455E-04	-3.237E-04	9.719E-06	5.076E-05	4.761E-04	-0.	6.50
4	0.0	3.00	-1.289E-03	3.957E-04	-6.211E-04	8.961E-06	4.111E-05	6.647E-04	-0.	6.50
5	0.0	4.05	-1.288E-03	3.839E-04	-9.034E-04	9.127E-06	4.907E-05	8.326E-04	-0.	6.50
6	0.0	5.97	-1.265E-03	2.578E-04	-1.612E-03	8.433E-06	5.240E-05	1.105E-03	-0.	6.50
7	0.0	8.00	-1.236E-03	2.077E-04	-2.525E-03	8.298E-06	6.701E-05	1.315E-03	-0.	6.49
8	0.0	10.05	-1.171E-03	2.538E-04	-3.856E-03	8.040E-06	8.571E-05	1.462E-03	-0.	6.49
9	0.0	11.96	-1.090E-03	3.396E-04	-5.285E-03	6.484E-06	8.282E-05	1.543E-03	-0.	6.50
10	0.0	13.94	-9.715E-04	4.443E-04	-6.829E-03	5.359E-06	4.349E-05	1.621E-03	0.	6.50
11	0.0	16.02	-8.129E-04	5.222E-04	-8.486E-03	4.201E-06	1.189E-05	1.704E-03	0.	6.50
12	0.0	18.09	-6.204E-04	5.491E-04	-1.025E-02	2.592E-06	-1.250E-05	1.762E-03	0.	6.50
13	0.0	0.00	-1.286E-03	5.450E-04	2.079E-04	9.448E-06	2.936E-05	1.005E-04	-0.	6.50
14	0.0	-1.04	-1.281E-03	5.079E-04	4.008E-04	8.821E-06	1.618E-05	-8.269E-05	-0.	6.50
15	0.0	-1.85	-1.289E-03	5.572E-04	6.284E-04	8.976E-06	8.778E-06	-2.367E-04	-0.	6.50
16	0.0	-3.07	-1.285E-03	5.756E-04	8.609E-04	8.555E-06	-9.242E-06	-4.219E-04	-0.	6.50
17	0.0	-3.89	-1.271E-03	6.192E-04	1.180E-03	8.340E-06	-1.768E-05	-5.981E-04	-0.	6.50
18	0.0	-6.02	-1.266E-03	7.449E-04	1.915E-03	7.920E-06	-1.260E-04	-8.766E-04	-0.	6.50
19	0.0	-8.04	-1.265E-03	9.532E-04	2.759E-03	1.085E-05	-2.115E-04	-1.076E-03	-0.	6.50
20	0.0	-9.98	-1.235E-03	1.335E-03	3.941E-03	1.418E-05	-3.515E-04	-1.215E-03	-0.	6.49
21	0.0	-12.02	-1.195E-03	1.837E-03	5.380E-03	1.643E-05	-5.484E-04	-1.290E-03	-0.	6.50
22	0.0	-13.97	-1.119E-03	2.259E-03	7.153E-03	1.512E-05	-7.313E-04	-1.351E-03	-0.	6.49
23	0.0	-15.99	-1.027E-03	2.536E-03	8.746E-03	1.172E-05	-8.732E-04	-1.394E-03	-0.	6.50
24	0.0	-17.62	-9.225E-04	2.924E-03	1.035E-02	7.938E-06	-1.009E-03	-1.419E-03	-0.	6.50
25	0.0	0.00	-1.298E-03	4.410E-04	1.952E-04	8.488E-06	-3.241E-06	9.609E-05	-0.	6.49
26	0.0	2.00	-1.293E-03	3.926E-04	-2.340E-04	8.799E-06	1.837E-05	4.432E-04	-0.	6.49
27	0.0	4.03	-1.275E-03	3.689E-04	-7.843E-04	9.305E-06	3.465E-05	7.825E-04	-0.	6.50
28	0.0	-1.97	-1.286E-03	5.255E-04	6.600E-04	8.423E-06	-2.109E-05	-2.771E-04	-0.	6.50
29	0.0	-4.01	-1.283E-03	6.287E-04	1.163E-03	8.738E-06	-3.376E-05	-6.097E-04	-0.	6.50
30	5.0	-4.10	-1.275E-03	6.219E-04	6.688E-04	8.465E-06	-4.016E-05	-8.355E-04	-0.	6.50
31	5.0	-2.01	-1.290E-03	4.881E-04	5.745E-05	7.645E-06	-1.838E-05	-4.466E-04	-0.	6.50
32	5.0	0.11	-1.305E-03	4.551E-04	-3.418E-04	8.531E-06	1.827E-06	-9.316E-05	-0.	6.50
33	5.0	2.05	-1.285E-03	4.500E-04	-7.680E-04	9.620E-06	3.812E-05	2.640E-04	-0.	6.50
34	5.0	3.99	-1.262E-03	3.226E-04	-1.322E-03	9.103E-06	4.177E-05	5.834E-04	-0.	6.50
35	10.0	-4.10	-1.334E-03	6.021E-04	2.512E-04	8.056E-06	-2.146E-05	-1.041E-03	-0.	6.49
36	10.0	-2.00	-1.341E-03	5.335E-04	-3.597E-04	8.103E-06	-2.868E-06	-6.781E-04	-0.	6.49
37	10.0	0.04	-1.364E-03	4.689E-04	-8.074E-04	8.287E-06	1.136E-05	-3.060E-04	-0.	6.49
38	10.0	2.06	-1.331E-03	3.915E-04	-1.266E-03	9.051E-06	2.886E-05	3.074E-05	-0.	6.50
39	10.0	3.99	-1.322E-03	3.811E-04	-1.841E-03	9.275E-06	4.779E-05	3.452E-04	-0.	6.49
40	15.0	-4.10	-1.393E-03	6.815E-04	-2.488E-04	6.645E-06	-4.196E-05	-1.245E-03	-0.	6.49
41	15.0	-2.05	-1.427E-03	5.694E-04	-8.853E-04	6.151E-06	-1.652E-05	-8.616E-04	-0.	6.49
42	15.0	0.14	-1.436E-03	4.899E-04	-1.296E-03	6.245E-06	-5.905E-06	-5.318E-04	-0.	6.50
43	15.0	2.09	-1.423E-03	4.616E-04	-1.824E-03	8.235E-06	4.350E-05	-1.724E-04	-0.	6.50
44	15.0	3.94	-1.412E-03	4.321E-04	-2.432E-03	8.018E-06	4.735E-05	1.313E-04	0.	6.50
46	-5.0	-4.04	-1.274E-03	6.433E-04	1.740E-03	1.081E-05	-3.137E-05	-4.076E-04	0.	6.49
47	-5.0	-2.06	-1.290E-03	5.336E-04	1.129E-03	1.017E-05	-1.065E-05	-6.802E-05	-0.	6.50
48	-5.0	0.19	-1.317E-03	4.784E-04	6.658E-04	9.800E-06	-2.572E-06	3.201E-04	-0.	6.50
49	-5.0	2.06	-1.299E-03	4.579E-04	1.794E-04	1.058E-05	2.536E-05	6.673E-04	-0.	6.50
50	-5.0	-0.04	-1.364E-03	4.714E-04	7.102E-04	9.973E-06	-5.093E-06	2.842E-04	-0.	6.49
51	-5.0	2.07	-1.353E-03	4.112E-04	1.933E-04	1.061E-05	2.420E-05	6.757E-04	-0.	6.49
52	-5.0	4.01	-1.348E-03	4.064E-04	-3.780E-04	1.112E-05	4.758E-05	1.013E-03	-0.	6.49
53	-10.0	-3.98	-1.355E-03	6.433E-04	2.227E-03	1.095E-05	-2.496E-05	-1.832E-04	-0.	6.49
54	-10.0	-1.96	-1.368E-03	5.209E-04	1.543E-03	9.863E-06	-1.716E-05	1.816E-04	-0.	6.49
55	-10.0	0.21	-1.374E-03	4.536E-04	1.135E-03	1.025E-05	-5.209E-06	5.263E-04	-0.	6.50
56	-10.0	1.91	-1.362E-03	4.255E-04	6.945E-04	1.067E-05	2.037E-05	8.439E-04	-0.	6.50
57	-10.0	4.09	-1.354E-03	3.837E-04	8.970E-05	1.102E-05	4.680E-05	1.225E-03	-0.	6.50
59	-15.0	-4.00	-1.490E-03	6.534E-04	2.789E-03	1.193E-05	-3.495E-05	4.916E-06	-0.	6.50
60	-15.0	-1.96	-1.484E-03	5.045E-04	2.084E-03	1.079E-05	-1.463E-05	3.782E-04	-0.	6.50
61	-15.0	-0.06	-1.492E-03	5.577E-04	1.758E-03	1.191E-05	1.923E-05	6.827E-04	-0.	6.50
62	-15.0	2.10	-1.482E-03	4.196E-04	1.241E-03	1.185E-05	3.282E-05	1.077E-03	-0.	6.50
63	-15.0	0.03	-1.472E-03	4.880E-04	1.732E-03	1.125E-05	-8.680E-06	6.931E-04	-0.	6.49
64	-15.0	1.98	-1.450E-03	4.364E-04	1.211E-03	1.177E-05	2.148E-05	1.082E-03	-0.	6.49
65	-15.0	4.00	-1.450E-03	3.693E-04	6.347E-04	1.164E-05	3.075E-05	1.412E-03	-0.	6.49

POINT	STERN PLANE ANGLE	ATTACK ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
66	-15.0	4.00	-1.444E-03	3.916E-04	6.243E-04	1.171E-05	3.403E-05	1.413E-03	-0.	6.50

MODEL MODEL 5470 CONFIGURATION 2
HORIZONTAL PLANE

POINT	STERN PLANE ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
67	0.0	0.00	-1.259E-03	-7.860E-05	3.750E-04	9.243E-06	1.055E-04	3.709E-05	-0.	6.50
68	0.0	1.03	-1.256E-03	4.830E-04	3.860E-04	2.122E-05	4.059E-04	1.114E-05	-0.	6.51
69	0.0	2.08	-1.237E-03	8.967E-04	4.359E-04	2.939E-05	5.885E-04	2.346E-05	-0.	6.50
70	0.0	2.94	-1.214E-03	1.447E-03	5.691E-04	4.067E-05	8.419E-04	5.123E-05	-0.	6.50
71	0.0	3.93	-1.179E-03	1.991E-03	7.521E-04	5.199E-05	1.078E-03	7.410E-05	0.	6.50
72	0.0	6.01	-1.093E-03	3.316E-03	1.155E-03	7.611E-05	1.459E-03	1.498E-04	0.	6.50
73	0.0	8.00	-9.891E-04	4.776E-03	1.930E-03	1.012E-04	1.781E-03	2.600E-04	0.	6.50
74	0.0	10.05	-8.382E-04	6.558E-03	2.866E-03	1.305E-04	2.085E-03	4.166E-04	-0.	6.50
75	0.0	11.97	-6.574E-04	8.475E-03	3.834E-03	1.615E-04	2.310E-03	5.385E-04	-0.	6.50
76	0.0	13.94	-4.248E-04	1.052E-02	4.767E-03	1.927E-04	2.515E-03	6.342E-04	-0.	6.50
77	0.0	13.95	-4.324E-04	1.057E-02	4.751E-03	1.939E-04	2.517E-03	6.200E-04	-0.	6.50
78	0.0	16.03	-1.631E-04	1.290E-02	5.704E-03	2.298E-04	2.717E-03	6.375E-04	0.	6.50
80	0.0	18.07	-2.811E-04	1.536E-02	7.137E-03	2.374E-04	2.733E-03	8.028E-04	-0.	6.50
81	0.0	18.08	-2.858E-04	1.520E-02	7.029E-03	2.319E-04	2.757E-03	7.685E-04	-0.	6.50
82	0.0	0.00	-1.323E-03	-9.696E-05	4.186E-04	8.677E-06	1.045E-04	2.440E-05	-0.	6.50
83	0.0	-1.04	-1.306E-03	-5.863E-04	4.799E-04	-1.971E-06	-1.551E-04	4.777E-05	0.	6.50
84	0.0	-1.95	-1.325E-03	-1.001E-03	5.726E-04	-9.981E-06	-3.412E-04	6.789E-05	-0.	6.50
85	0.0	-3.07	-1.320E-03	-1.586E-03	6.937E-04	-2.113E-05	-5.887E-04	1.140E-04	-0.	6.50
86	0.0	-3.98	-1.295E-03	-2.185E-03	9.726E-04	-3.252E-05	-8.361E-04	1.594E-04	-0.	6.50
87	0.0	-5.92	-1.246E-03	-3.408E-03	1.506E-03	-5.347E-05	-1.184E-03	3.175E-04	-0.	6.50
88	0.0	-8.01	-1.186E-03	-4.866E-03	2.474E-03	-7.532E-05	-1.509E-03	5.060E-04	-0.	6.50
89	0.0	-9.97	-1.095E-03	-6.613E-03	3.581E-03	-9.869E-05	-1.792E-03	7.539E-04	0.	6.50
90	0.0	-12.02	-9.485E-04	-8.774E-03	4.923E-03	-1.286E-04	-2.040E-03	1.009E-03	-0.	6.50
91	0.0	-13.44	-7.783E-04	-1.064E-02	6.048E-03	-1.560E-04	-2.200E-03	1.203E-03	0.	6.50
92	0.0	-0.00	-1.301E-03	-1.034E-04	4.248E-04	8.568E-06	9.097E-05	2.501E-05	-0.	6.50
93	0.0	2.11	-1.315E-03	9.067E-04	5.075E-04	2.997E-05	6.030E-04	1.916E-05	-0.	6.47
94	0.0	3.92	-1.239E-03	1.955E-03	7.724E-04	5.157E-05	1.073E-03	7.367E-05	0.	6.49
95	0.0	-2.05	-1.323E-03	-1.011E-03	6.056E-04	-1.121E-05	-3.706E-04	8.262E-05	0.	6.49
96	0.0	-4.03	-1.289E-03	-2.207E-03	1.018E-03	-3.354E-05	-8.586E-04	1.765E-04	0.	6.49
97	5.0	0.16	-1.279E-03	4.794E-04	4.093E-04	9.665E-06	-6.351E-05	2.356E-05	0.	6.49
98	5.0	2.09	-1.244E-03	1.311E-03	4.473E-04	2.870E-05	3.982E-04	2.840E-05	0.	6.49
99	5.0	4.09	-1.181E-03	2.424E-03	7.644E-04	5.055E-05	8.728E-04	8.233E-05	-0.	6.49
100	5.0	-2.05	-1.253E-03	-5.238E-04	6.119E-04	-1.176E-05	-5.767E-04	5.176E-05	-0.	6.49
101	5.0	-1.84	-1.351E-03	-4.573E-04	5.545E-04	-1.015E-05	-5.391E-04	6.450E-05	-0.	6.49
102	5.0	-3.99	-1.313E-03	-1.659E-03	9.883E-04	-3.315E-05	-1.027E-03	1.508E-04	-0.	6.50
103	10.0	0.11	-1.380E-03	9.165E-04	4.185E-04	8.619E-06	-2.676E-04	2.648E-05	-0.	6.49
104	10.0	2.08	-1.315E-03	1.843E-03	4.584E-04	2.788E-05	2.116E-04	2.460E-05	0.	6.49
105	10.0	4.09	-1.245E-03	2.903E-03	8.043E-04	4.929E-05	6.813E-04	8.459E-05	0.	6.49
106	10.0	-2.00	-1.328E-03	-7.015E-05	5.733E-04	-1.230E-05	-7.698E-04	6.264E-05	0.	6.50
107	10.0	-4.09	-1.298E-03	-1.246E-03	9.538E-04	-3.510E-05	-1.235E-03	1.564E-04	0.	6.50
108	15.0	0.21	-1.449E-03	1.480E-03	4.367E-04	7.868E-06	-4.706E-04	3.201E-05	-0.	6.49
109	15.0	2.03	-1.412E-03	2.360E-03	4.942E-04	2.719E-05	1.482E-05	1.982E-05	-0.	6.49
110	15.0	4.09	-1.345E-03	3.490E-03	8.497E-04	4.788E-05	4.720E-04	9.149E-05	-0.	6.49
111	15.0	-2.05	-1.432E-03	4.833E-04	5.951E-04	-1.228E-05	-9.703E-04	5.092E-05	0.	6.50
112	15.0	-3.99	-1.400E-03	-7.235E-04	9.996E-04	-3.526E-05	-1.418E-03	1.514E-04	0.	6.49

MODEL MODEL 5470 CONFIGURATION 2
HORIZONTAL PLANE

POINT	RUDDER ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
113	-5.0	-0.00	-1.297E-03	-6.555E-04	3.881E-04	9.794E-06	2.971E-04	3.714E-05	-0.	6.49
114	-5.0	2.09	-1.263E-03	3.333E-04	4.379E-04	3.109E-05	8.144E-04	2.953E-05	-0.	6.50
115	-5.0	4.09	-1.203E-03	1.457E-03	7.494E-04	5.397E-05	1.288E-03	7.291E-05	0.	6.50
116	-5.0	-2.05	-1.288E-03	-1.522E-03	5.522E-04	-8.549E-06	-1.345E-04	7.245E-05	-0.	6.50
117	-5.0	-4.10	-1.252E-03	-2.706E-03	9.844E-04	-3.047E-05	-6.236E-04	1.692E-04	0.	6.50
118	-10.0	-0.00	-1.359E-03	-1.141E-03	4.218E-04	1.020E-05	4.914E-04	3.222E-05	-0.	6.49
119	-10.0	2.09	-1.327E-03	-1.929E-04	4.204E-04	3.020E-05	9.845E-04	3.394E-05	0.	6.50
120	-10.0	4.09	-1.276E-03	1.070E-03	7.734E-04	5.569E-05	1.487E-03	6.755E-05	0.	6.50
121	-10.0	-2.05	-1.348E-03	-2.038E-03	5.449E-04	-8.617E-06	5.499E-05	8.218E-05	-0.	6.50
122	-10.0	-3.99	-1.322E-03	-3.207E-03	9.834E-04	-2.950E-05	-4.301E-04	1.839E-04	0.	6.50
123	-15.0	0.00	-1.522E-03	-1.620E-03	4.157E-04	1.106E-05	7.091E-04	1.791E-05	-0.	6.49
124	-15.0	2.11	-1.488E-03	-6.878E-04	4.545E-04	3.185E-05	1.210E-03	1.491E-05	0.	6.50
125	-15.0	3.93	-1.422E-03	5.185E-04	7.637E-04	5.642E-05	1.655E-03	5.410E-05	0.	6.50
126	-15.0	-2.05	-1.517E-03	-2.503E-03	5.471E-04	-6.797E-06	2.742E-04	6.556E-05	0.	6.50
127	-15.0	-4.10	-1.497E-03	-3.798E-03	1.012E-03	-2.815E-05	-2.257E-04	2.170E-04	0.	6.50

MODEL MODEL 5470 CONFIGURATION 5

HORIZONTAL PLANE

POINT	RUDDER ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
128	0.0	0.00	-1.133E-03	-1.693E-04	3.970E-04	5.702E-06	6.711E-05	-4.219E-06	-0.	6.50
129	0.0	1.06	-1.145E-03	6.609E-05	2.883E-04	6.213E-06	3.143E-04	-2.916E-05	-0.	6.50
130	0.0	2.11	-1.128E-03	2.535E-04	2.332E-04	6.653E-06	4.768E-04	-3.515E-05	-0.	6.50
131	0.0	3.03	-1.145E-03	4.492E-04	2.077E-04	7.288E-06	6.856E-04	-5.604E-05	-0.	6.50
132	0.0	3.94	-1.140E-03	7.410E-04	1.331E-04	7.848E-06	8.720E-04	-5.654E-05	-0.	6.50
133	0.0	6.08	-1.114E-03	1.369E-03	4.308E-05	8.564E-06	1.184E-03	-7.289E-05	-0.	6.50
134	0.0	8.00	-1.092E-03	2.253E-03	-3.542E-05	8.563E-06	1.405E-03	-1.060E-04	-0.	6.50
135	0.0	10.05	-1.038E-03	3.534E-03	-1.333E-04	8.048E-06	1.569E-03	-1.341E-04	-0.	6.50
136	0.0	11.97	-9.470E-04	4.907E-03	-1.347E-04	6.376E-06	1.700E-03	-1.422E-04	0.	6.50
137	0.0	13.99	-8.426E-04	6.251E-03	-1.347E-04	4.551E-06	1.818E-03	-1.518E-04	-0.	6.50
138	0.0	15.95	-7.288E-04	7.728E-03	-1.230E-04	3.248E-06	1.965E-03	-1.410E-04	-0.	6.50
139	0.0	18.11	-5.442E-04	9.414E-03	-8.352E-05	1.183E-06	2.097E-03	-1.248E-04	0.	6.50
140	0.0	0.20	-1.122E-03	-1.589E-04	3.659E-04	5.407E-06	9.912E-05	-1.929E-05	-0.	6.50
141	0.0	-1.03	-1.125E-03	-3.340E-04	4.116E-04	4.850E-06	-1.184E-04	-1.511E-05	0.	6.50
142	0.0	-1.95	-1.135E-03	-5.135E-04	4.343E-04	4.289E-06	-2.832E-04	2.086E-05	-0.	6.50
143	0.0	-3.07	-1.135E-03	-6.945E-04	5.033E-04	3.838E-06	-4.975E-04	3.549E-05	-0.	6.50
144	0.0	-3.97	-1.129E-03	-9.185E-04	5.673E-04	3.356E-06	-7.088E-04	4.855E-05	0.	6.50
145	0.0	-5.92	-1.134E-03	-1.512E-03	6.686E-04	3.928E-06	-1.029E-03	1.040E-04	-0.	6.50
146	0.0	-8.00	-1.128E-03	-2.367E-03	8.738E-04	7.203E-06	-1.262E-03	1.709E-04	-0.	6.50
147	0.0	-9.98	-1.112E-03	-3.461E-03	1.164E-03	1.153E-05	-1.429E-03	2.487E-04	-0.	6.50
148	0.0	-12.02	-1.059E-03	-4.896E-03	1.568E-03	1.522E-05	-1.572E-03	3.971E-04	-0.	6.50
149	0.0	-13.96	-9.862E-04	-6.350E-03	1.954E-03	1.553E-05	-1.688E-03	5.274E-04	-0.	6.50
150	0.0	-15.99	-8.923E-04	-8.100E-03	2.316E-03	1.334E-05	-1.815E-03	6.716E-04	-0.	6.50
151	0.0	-18.01	-7.208E-04	-9.869E-03	2.609E-03	1.035E-05	-1.909E-03	7.517E-04	-0.	6.50

MODEL MODEL 5470 CONFIGURATION 3

HORIZONTAL PLANE

POINT	RUDDER ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
152	0.0	0.20	-1.061E-03	-9.918E-05	3.707E-05	1.077E-06	9.760E-05	-1.061E-04	-0.	6.50
153	0.0	1.06	-1.061E-03	2.080E-05	-8.322E-06	1.144E-06	3.459E-04	-1.129E-04	0.	6.50
154	0.0	2.08	-1.045E-03	1.335E-04	-2.890E-05	1.455E-06	5.174E-04	-1.129E-04	-0.	6.50
155	0.0	3.00	-1.056E-03	3.214E-04	-4.840E-06	1.638E-06	7.709E-04	-1.060E-04	-0.	6.50
156	0.0	4.07	-1.061E-03	4.485E-04	-1.507E-05	1.896E-06	9.959E-04	-1.006E-04	0.	6.50
157	0.0	6.03	-1.059E-03	8.860E-04	-3.852E-05	2.014E-06	1.385E-03	-7.105E-05	0.	6.50
158	0.0	8.00	-1.069E-03	1.536E-03	-4.721E-05	1.921E-06	1.708E-03	-5.583E-05	-0.	6.50
159	0.0	10.05	-1.049E-03	2.450E-03	-3.691E-05	1.297E-06	2.008E-03	-3.596E-05	-0.	6.50
160	0.0	12.03	-9.940E-04	3.462E-03	-8.193E-06	5.794E-07	2.266E-03	-5.185E-05	0.	6.50
161	0.0	13.94	-9.138E-04	4.586E-03	1.717E-05	-3.723E-07	2.511E-03	-4.269E-05	-0.	6.50
163	0.0	16.03	-8.087E-04	5.864E-03	1.122E-04	-9.640E-07	2.750E-03	3.100E-06	0.	6.50
164	0.0	18.11	-6.698E-04	7.355E-03	3.170E-04	-2.101E-06	2.986E-03	3.457E-05	0.	6.50
165	0.0	0.12	-1.051E-03	-8.163E-05	3.398E-05	6.810E-07	6.960E-05	-9.971E-05	0.	6.50
166	0.0	-1.03	-1.054E-03	-2.057E-04	2.288E-05	5.143E-07	-1.599E-04	-8.796E-05	0.	6.50
167	0.0	-1.95	-1.069E-03	-2.920E-04	2.325E-05	4.959E-08	-3.499E-04	-9.162E-05	-0.	6.50
168	0.0	-3.07	-1.057E-03	-4.079E-04	7.564E-05	-4.262E-07	-5.977E-04	-8.617E-05	0.	6.50
169	0.0	-4.11	-1.046E-03	-5.922E-04	1.321E-0[illegible]	-5.770E-07	-8.640E-04	-7.674E-05	-0.	6.50
170	0.0	-5.93	-1.061E-03	-9.473E-04	2.521E-0[illegible]	-1.097E-06	-1.226E-03	-3.958E-05	-0.	6.50
171	0.0	-8.00	-1.079E-03	-1.553E-03	3.832E-04	-1.197E-06	-1.571E-03	1.476E-05	-0.	6.50
172	0.0	-9.99	-1.079E-03	-2.337E-03	5.502E-04	-1.386E-06	-1.875E-03	5.903E-05	0.	6.50
173	0.0	-12.02	-1.058E-03	-3.411E-03	6.381E-04	-1.518E-06	-2.149E-03	7.853E-05	0.	6.50
174	0.0	-13.98	-1.014E-03	-4.569E-03	7.519E-04	-1.658E-06	-2.404E-03	1.002E-04	-0.	6.50
175	0.0	-16.18	-9.468E-04	-5.958E-03	8.790E-04	-1.678E-06	-2.668E-03	9.940E-05	-0.	6.50
176	0.0	-18.05	-8.524E-04	-7.438E-03	8.988E-04	-1.698E-06	-2.939E-03	8.763E-05	0.	6.50

MODEL MODEL 5470 CONFIGURATION 4
HORIZONTAL PLANE

POINT	RUDDER ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
177	0.0	0.17	-1.162E-03	-4.706E-05	-1.947E-05	2.912E-06	6.406E-05	-7.449E-05	-0.	6.49
178	0.0	1.01	-1.156E-03	2.867E-04	8.814E-06	1.344E-05	2.981E-04	-1.016E-04	-0.	6.50
179	0.0	1.99	-1.152E-03	7.010E-04	6.388E-05	2.543E-05	5.681E-04	-4.844E-05	-0.	6.50
180	0.0	3.02	-1.138E-03	1.075E-03	1.662E-04	3.735E-05	8.364E-04	-5.573E-05	0.	6.50
181	0.0	4.01	-1.125E-03	1.505E-03	3.902E-04	5.014E-05	1.108E-03	-3.767E-05	-0.	6.50
182	0.0	6.01	-1.084E-03	2.512E-03	8.569E-04	7.613E-05	1.613E-03	4.322E-05	0.	6.50
183	0.0	8.12	-1.07[illegible]E-03	3.603E-03	1.413E-03	9.863E-05	2.047E-03	1.399E-04	0.	6.50
184	0.0	7.91	-1.[illegible]40E-03	3.539E-03	1.407E-03	9.773E-05	2.039E-03	1.248E-04	0.	6.50
185	0.0	9.94	-9.172E-04	4.923E-03	2.228E-03	1.275E-04	2.494E-03	2.211E-04	0.	6.50
186	0.0	11.95	-7.725E-04	6.386E-03	3.041E-03	1.557E-04	2.893E-03	2.836E-04	0.	6.50
187	0.0	13.92	-6.004E-04	8.030E-03	3.919E-03	1.843E-04	3.282E-03	3.527E-04	0.	6.50
188	0.0	16.04	-4.014E-04	9.898E-03	4.812E-03	2.156E-04	3.676E-03	3.589E-04	-0.	6.50
189	0.0	18.05	-6.042E-04	1.131E-02	6.061E-03	2.212E-04	3.865E-03	4.238E-04	0.	6.50
190	0.0	0.00	-1.160E-03	-1.391E-04	-9.810E-06	-2.825E-07	1.044E-06	-8.286E-05	0.	6.50
191	0.0	-1.04	-1.152E-03	-5.142E-04	8.884E-05	-1.199E-05	-2.733E-04	-9.141E-05	-0.	6.50
192	0.0	-1.96	-1.156E-03	-9.258E-04	1.350E-04	-2.301E-05	-5.215E-04	-5.587E-05	0.	6.50
193	0.0	-3.07	-1.155E-03	-1.337E-03	2.938E-04	-3.578E-05	-7.957E-04	-3.292E-05	0.	6.50
194	0.0	-4.10	-1.132E-03	-1.888E-03	5.403E-04	-5.074E-05	-1.101E-03	9.325E-06	0.	6.50
195	0.0	-6.01	-1.092E-03	-2.942E-03	1.156E-03	-7.831E-05	-1.636E-03	9.820E-05	-0.	6.50
196	0.0	-8.03	-1.052E-03	-3.993E-03	1.829E-03	-1.029E-04	-2.071E-03	2.060E-04	0.	6.50
197	0.0	-10.08	-9.674E-04	-5.292E-03	2.631E-03	-1.294E-04	-2.487E-03	2.724E-04	0.	6.50
198	0.0	-12.02	-8.301E-04	-6.862E-03	3.594E-03	-1.610E-04	-2.923E-03	3.107E-04	0.	6.50
199	0.0	-13.94	-6.611E-04	-8.631E-03	4.512E-03	-1.933E-04	-3.343E-03	3.384E-04	0.	6.50
200	0.0	-12.84	-7.482E-04	-7.769E-03	4.068E-03	-1.772E-04	-3.134E-03	3.294E-04	0.	6.50
201	0.0	-15.99	-4.609E-04	-1.043E-02	5.237E-03	-2.239E-04	-3.710E-03	2.917E-04	0.	6.50
202	0.0	-17.80	-5.697E-04	-1.197E-02	6.286E-03	-2.352E-04	-3.738E-03	1.893E-04	-0.	6.50

MODEL MODEL 5470 CONFIGURATION 6
HORIZONTAL PLANE

POINT	RUDDER ANGLE	DRIFT ANGLE	X'	Y'	Z'	K'	N'	M'	RPM	VEL
203	0.0	-0.00	-1.123E-03	-1.544E-04	3.717E-05	3.280E-07	6.780E-05	-1.191E-04	-0.	6.50
204	0.0	1.06	-1.123E-03	1.402E-05	2.776E-05	7.801E-07	3.637E-04	-1.151E-04	-0.	6.50
205	0.0	2.08	-1.125E-03	1.067E-04	-3.760E-05	1.159E-06	5.624E-04	-1.049E-04	0.	6.50
206	0.0	3.01	-1.119E-03	3.069E-04	-9.593E-06	1.269E-06	7.987E-04	-1.159E-04	-0.	6.50
207	0.0	4.04	-1.112E-03	4.717E-04	-3.060E-05	1.442E-06	1.014E-03	-1.074E-04	-0.	6.50
208	0.0	5.96	-1.120E-03	9.390E-04	-5.414E-05	1.377E-06	1.383E-03	-9.727E-05	0.	6.50
209	0.0	8.00	-1.124E-03	1.652E-03	-8.774E-05	1.021E-06	1.689E-03	-7.760E-05	0.	6.50
210	0.0	10.05	-1.101E-03	2.620E-03	-8.961E-05	2.463E-07	1.947E-03	-5.674E-05	-0.	6.50
211	0.0	12.06	-1.061E-03	3.729E-03	-7.478E-05	-4.020E-07	2.159E-03	-4.799E-05	-0.	6.50
212	0.0	13.95	-9.783E-04	4.942E-03	-4.842E-05	-1.171E-06	2.362E-03	-2.958E-05	-0.	6.50
213	0.0	16.11	-8.656E-04	6.411E-03	-1.836E-05	-2.615E-06	2.549E-03	-1.896E-05	-0.	6.50
214	0.0	1.06	-1.146E-03	-2.567E-05	2.225E-05	5.537E-07	3.528E-04	-1.127E-04	-0.	6.50
215	0.0	18.07	-7.173E-04	7.957E-03	3.708E-05	-3.621E-06	2.741E-03	-1.417E-05	0.	6.50
216	0.0	0.14	-1.140E-03	-1.314E-04	4.313E-05	1.490E-07	9.656E-05	-1.143E-04	-0.	6.50
217	0.0	-1.05	-1.146E-03	-2.157E-04	1.198E-04	-3.274E-07	-1.381E-04	-1.374E-04	-0.	6.50
218	0.0	-1.96	-1.149E-03	-3.148E-04	1.247E-04	-3.549E-07	-3.383E-04	-1.367E-04	-0.	6.50
219	0.0	-3.08	-1.152E-03	-4.926E-04	1.298E-04	-7.207E-07	-5.634E-04	-1.146E-04	-0.	6.50
220	0.0	-3.89	-1.141E-03	-7.043E-04	1.353E-04	-1.104E-06	-7.859E-04	-1.092E-04	-0.	6.50
221	0.0	-5.93	-1.139E-03	-1.061E-03	2.912E-04	-1.372E-06	-1.148E-03	-7.459E-05	0.	6.50
222	0.0	-8.00	-1.141E-03	-1.704E-03	3.750E-04	-1.392E-06	-1.471E-03	-4.899E-05	0.	6.50
223	0.0	-9.99	-1.149E-03	-2.575E-03	4.203E-04	-1.188E-06	-1.747E-03	-1.301E-05	0.	6.50
224	0.0	-11.90	-1.125E-03	-3.733E-03	3.843E-04	-1.433E-06	-1.963E-03	-9.769E-06	-0.	6.50
225	0.0	-14.03	-1.069E-03	-5.053E-03	4.299E-04	-1.511E-06	-2.162E-03	-3.673E-05	-0.	6.50
226	0.0	-15.91	-1.000E-03	-6.413E-03	4.996E-04	-1.220E-06	-2.337E-03	-3.596E-05	-0.	6.50
227	0.0	-18.00	-9.165E-04	-8.108E-03	4.630E-04	-8.348E-07	-2.528E-03	-4.371E-05	-0.	6.50

APPENDIX C

UNCERTAINTY ANALYSIS

UNCERTAINTY ANALYSIS

INTRODUCTION

In various engineering fields there have been efforts recently to develop a rigorous approach to analyzing the accuracy of experiments. The purpose is to emphasize that all experiments are subject to variations in the relevant physical parameters and their measurement which cannot be controlled by the engineer, and that bounds on the possible variation in reported results should be stated and substantiated.

This approach has been defined as "uncertainty analysis." In uncertainty analysis two contributions to the total uncertainty of results are identified which apply to captive-model stability and control experiments conducted at DTRC. The first type is called bias, and it is the most difficult to quantify. Bias is defined as any effect which is held constant throughout the experiment and which leads to a constant variation of the results from the true value. An example of bias is the error which occurs in calibrating instrumentation. The second type of uncertainty is defined as the precision error, and is the random scatter of results which is seen when experiments are repeated under nominally identical conditions. The relationship between bias and precision errors, and the uncertainty analysis for captive-model stability and control experiments are discussed below.

CAPTIVE-MODEL EXPERIMENTS

Sources of bias errors include (1) 4-inch block gages (variable reluctance transducers) used to measure the hydrodynamic forces and moments, (2) Tracor Hydronautics, Incorporated signal conditioners, (2) 6-Hz low-pass filters, (3) Preston 15-bit analog-to-digital converter, (4) Elgar power supply for the signal conditioners, (5) misalignment of the apparatus used to calibrate the 4-inch block gages, (6) misalignment of the gages in the calibration stand, (7) misalignment of the gages in the model, (8) the sensitivity of a gage to forces applied perpendicular to its axis, (9) misalignment of the channel in the model to which the gages are attached, (10) errors in the fabrication of the model, (11) misalignment of the model in attaching it to the towing carriage, (12) constant errors in setting the carriage speed, tilt table angle, control surface angle, propeller rpm, phase angle between the struts, frequency of oscillation, and the sine-cosine potentiometer, (13) unknown changes in the water temperature which affects the density and viscosity, (14) currents in the basin, and (15) errors in ballasting the model for neutral buoyancy and trim.

Sources of precision errors include (1) mistakes in setting carriage speed, tilt table angle, control surface angle, propeller rpm, phase angle between the struts, oscillation frequency, and sine-cosine potentiometer, (2) irregularities in the rails on which the towing carriage travels (the vertical acceleration that is induced causes random errors in the data and affects repeatability), (3) changes in the alignment of the model from test to test, (4) unanticipated unsteady conditions while data are being collected, (5)

unknown changes in the water temperature which affects the density and viscosity, (6) unknown water disturbances, and (7) interpretation of data, fairing of curves through the data, determination of slopes, choice of mathematical fit of data, and choice of data to be fitted.

Most of the bias and precision errors are negligible based on observations, tests, and analyses performed over a period of many years. However, the following bias and precision errors can be significant: (1) Changes in gage calibration from time to time probably results in a bias error of about 0.5 percent, (2) fabrication of the appendages for the model, (3) incorrectly setting model test conditions, for example, tilt table angle, speed, propeller rpm, control surface angles, phase angles between the struts, frequency of oscillation, and the position of the sine-cosine potentiometer, (4) nonlinearity in the gage calibration probably results in a precision error of about 0.5 percent, (5) irregularities in the rails in the towing basin, and (6) interpretation of the hydrodynamic force and moment data.

In order to determine the multiple calibration precision error, a 4-inch block gage was calibrated thirty times over a three-day period. The gage was calibrated by placing 5 and 10 pounds weights, each having an accuracy of 0.01 percent, to a pan which was attached with a 5 to 1 lever arm to the gage. The maximum load applied to the gage was 300 pounds, both in the positive and negative directions. After each calibration the gage was removed from the calibration stand, and then reattached to the stand in a different orientation. For the reference calibration the span pot of the Multi-T amplifier was set at 2.118 volts to give a sensitivity of approximately 30 millivolt per pound. For the 30 calibrations which followed, the span pot on the Multi-T amplifier was set to 2.118 volts each time which resulted in the following sensitivities: 30.27, 30.28, 30.35, 30.36, 30.45, 30.34, 30.39, 30.34, 30.38, 30.36, 30.40, 30.46, 30.38, 30.35, 30.42, 30.43, 30.39, 30.45, 30.40, 30.46, 30.46, 30.36, 30.44, 30.32, 30.33, 30.30, 30.35, 30.33, 30.32, and 30.23. The sample mean of these thirty sensitivities is 30.37 and the sample standard deviation is 0.060.

The relationship between the sample standard deviation s and the population standard deviation s_* can be determined from the chi-square probability distribution. For a sample size n, the random variable u having a chi-square probability distribution is given by

$$u = (n - 1)s^2/s_*^2$$

For example, if the sample size is 30, then the degrees of freedom are 29, and from a table for the chi-square distribution the probability of the random variable u being between $u_1 = 17.708$ and infinity is 0.95 and between $u_1 =$ 42.557 and infinity is 0.05. Using the relationship

$$s_*^2 = (n - 1)s^2/u_1$$

the population standard deviation is calculated to be in the following range for the given percent confidences:

Percent Confidence	s_{*min}	s_{*max}
99	0.045	0.089
95	0.048	0.081
90	0.050	0.077
80	0.052	0.073
60	0.055	0.068

The relationship between the sample mean m and the population mean m_* can be determined from the "t" distribution. For a given sample size n the random variable t having a "t" probability distribution is given by

$$t = (m - m_*)n^{1/2}/s$$

Based on a sample size of 30, from a table for the "t" distribution the probability of the random variable t being between t_1 = 1.699 and infinity is 0.05. Hence, the probability of t being between -1.699 and 1.699 is 0.90. Using the relationship

$$m_* = m + t_1 s/n^{1/2}$$

or

$$m_* = m - t_1 s/n^{1/2}$$

the population mean is calculated to be in the following range for the given percent confidences:

Percent Confidence	m_{*min}	m_{*max}
99	30.340	30.400
95	30.348	30.392
90	30.351	30.389
80	30.356	30.384
60	30.361	30.379

The 95 percent confidence limit for a sample of n measurements drawn from a Gaussian distribution can be defined as the precision limit P for the mean of the measurements, where

$$P = st_1/n^{1/2}$$

If there is no bias in the measurements, the uncertainty for the calibration is P/m. The values of m, s, t_1, n, and P/m are 30.37, 0.060, 2.045, 30, and 0.0007, respectively.

To develop an uncertainty analysis for a particular experiment, it must be based on the fact that the calibration of each 4-inch block gage is performed

only once before the test is begun. A typical recent block gage calibration indicated that the sample mean for the sensitivity was 29.76 millivolts per pound and the sample standard deviation for the sensitivity was 0.12 millivolt per pound for a sample size of 24 different applied loads to the gage. Hence, the value of t_1 was 2.069 and the value of P/m was 0.0017.

A potentiometer was used to measure the angle of the tilt table. The tilt table is used to set the model at an angle of attack or an angle of drift. The potentiometer was also calibrated before the experiments are begun. A typical calibration indicated that the sample mean for the sensitivity was 370.87 millivolts per degree and the sample standard deviation was 20.17 millivolt per degree for a sample size of 18 different angle settings. Hence, the value of t_1 was 2.110 and the value of P/m was 0.0270.

The stability and control derivatives are determined by reading the slope of the appropriate curve of force or moment with either body angle or control surface angle at a value of zero body angle or zero control surface angle, respectively. For example, the stability derivative Z_w' was read independently by 10 engineers. Based on these readings, the sample mean was -0.006489 and the sample standard deviation was -0.000262 for a sample size of 10. Hence, the value of t_1 was 2.262 and the value of P/m was 0.0289.

The uncertainty in the overall length of the model is estimated to be 1/16 inch in 13.9792 feet or 0.0004. The uncertainty in the carriage speed is estimated to be 0.01 knot in 6.5 knots or 0.0015. The uncertainty in the density is estimated to be 0.0006 $lb\text{-}sec^2/ft^4$ for a change of 3 degrees F in 1.9367 $lb\text{-}sec^2/ft^4$ or 0.0003.

The uncertainties in the individual variables propagate through the data reduction equations into the stability and control derivatives. For example, the stability derivative Z_w' is given by the following expression:

$$f = Z_w' = e_1/(e_2 e_3 e_4 e_4 e_5 e_5)$$

where e_1 is the change in the measured normal force in pounds, e_2 is the corresponding change in the measured angle of attack in radians, e_3 is half of the density in $lb\text{-}sec^2/ft^4$, e_4 is the length used for nondimensionalization in feet, and e_5 is the forward speed in feet per second.

The square of the value of the uncertainty in f is given by

$$U_f^2 = \ldots + (U_{ek}\, df/de_k)^2 + \ldots$$

where k is an index with values from 1 through 5, df/de_k are partial derivatives which are called absolute sensitivity coefficients, and U_{ek} are the values of the uncertainties in each e_k. The expression for f must be continuous and have continuous derivatives in the domain of interest. The measured variables e_k must be independent of one another, and the uncertainties in the measured variables must be independent of one another.

The partial derivatives are given by the following expressions:

$$df/de_1 = f/e_1$$

$$df/de_2 = -f/e_2$$

$$df/de_3 = -f/e_3$$

$$df/de_4 = -2f/e_4$$

$$df/de_5 = -2f/e_5$$

Since the value of the uncertainty in reading the slope of the curve of normal force with angle of attack is $U_{rf} = 0.0289f$, the value of the total uncertainty U_{tf} for the stability derivative Z_w' can be determined from the following expression:

$$U_{tf}^2 = U_f^2 + U_{rf}^2$$

The total uncertainties in the stability derivatives Z_w' and M_w' are calculated to be about 4 percent for both derivatives. A similar analysis for the sternplane control derivatives indicate that these total uncertainties are about 6 percent for both the normal force and pitching moment derivatives if the uncertainty in measuring the control surface angle is assumed to be 0.5 degree for a 10-degree deflection.

Although it is difficult at the present time to quantify all of the individual bias and precision errors, using the above analysis and the submarine stability and control data base, which includes a significant number of experiments which have been repeated, in some cases more than twice, the following overall uncertainty errors may be assigned to the experimental values of the stability and control derivatives for fully appended submarines: (1) static derivatives Z_w', M_w', Y_v', and N_v' 4 to 5 percent, (2) rotary derivatives Z_q', M_q', Y_r', and N_r' about 10 percent, (3) control derivatives 6 to 10 percent, and (4) added mass and moment of inertia derivatives $Z_{\dot{w}}'$, $M_{\dot{q}}'$, $Y_{\dot{v}}'$, and $N_{\dot{r}}'$ about 7 percent. The uncertainty error in calculating the nondimensional mass is about 2 percent.

Captive-model experiments have been performed with the same submarine model and with similar test procedures and instrumentation several months or years apart. The results from these repeat experiments includes inaccuracies in the test set-up, instrumentation, and data analysis, as well as environmental variations, and should not be confused with repeatability from run to run during a single test, which typically is much better. The rotary derivatives have, until recently, been measured on the Planar Motion Mechanism (PMM) by performing oscillation experiments (heaving, pitching, swaying, and yawing). These experiments are now often performed on the rotating arm, and the quality of this data appears to be better than the PMM data.

The uncertainty errors of the individual stability derivatives propagate into the margin of stability which is designated by the symbol G. The margin of stability is a function of four nondimensional stability derivatives, the nondimensional mass of the submarine, and the nondimensional longitudinal location of the center of gravity from the reference point. If these nondimensional quantities are designated by the symbols e_k, then the margin of stability has the following form:

$$G = 1 - e_1(e_2 + e_3)/[e_4(e_5 + e_6e_3)]$$

The square of the uncertainty in G is given by

$$\begin{aligned}(U_G/G)^2 = &(e_1/G)^2(dG/de_1)^2(U_{e1}/e_1)^2 \\ &+ (e_2/G)^2(dG/de_2)^2(U_{e2}/e_2)^2 \\ &+ (e_3/G)^2(dG/de_3)^2(U_{e3}/e_3)^2 \\ &+ (e_4/G)^2(dG/de_4)^2(U_{e4}/e_4)^2 \\ &+ (e_5/G)^2(dG/de_5)^2(U_{e5}/e_5)^2 \\ &+ (e_6/G)^2(dG/de_6)^2(U_{e6}/e_6)^2\end{aligned}$$

where dG/de_k are partial derivatives and U_{ek}/e_k are the uncertainties in each e_k. The partial derivatives are given by the following expressions:

$$dG/de_1 = -(e_2 + e_3)/(e_4e_7)$$

$$dG/de_2 = -e_1/(e_4e_7)$$

$$dG/de_3 = -e_1/(e_4e_7) + e_1(e_2 + e_3)e_6/(e_4e_7^2)$$

$$dG/de_4 = e_1(e_2 + e_3)/(e_4^2e_7)$$

$$dG/de_5 = e_1(e_2 + e_3)/(e_4e_7^2)$$

$$dG/de_6 = e_1(e_2 + e_3)e_3/(e_4e_7^2)$$

where

$$e_7 = e_5 + e_6e_3.$$

The uncertainty in G depends on the particular values of the nondimensional stability derivatives, the nondimensional mass, and the nondimensional longitudinal location of the center of gravity from the reference point.

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